Word length effects in the left and right cerebral hemispheres: The right visual field advantage.

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Word length effects in the left and right cerebral hemispheres: the Right Visual Field Advantage

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Abstract

It has long been known that word length has a larger influence on the recognition of words presented in the left visual field than the right visual field, an effect commonly referred to as the length by visual field interaction. The aim of the present thesis was to explore the neural and behavioural effects of the length by visual field interaction. In doing so, it was expected that the results would contribute to and extend the body of behavioural research in this area, particularly in regard to the hemispheric processing of words. Chapter One presents a general overview of the thesis; in Chapter Two, the nature of the right visual field advantage is reviewed, with particular reference to previous work that has demonstrated differential effects of word length in each of the cerebral hemispheres. Models that seek to account for visual field asymmetries are also reviewed. Chapter Three outlines the key methods adopted in the thesis, namely, the divided visual field task and the use of event-related potentials. Chapters Four and Five present the results of two experiments that explored the neural effect of increasing word length in each of the hemispheres. The results provided ERP evidence of early processing dissociations between the hemispheres in terms of words and non-words of different lengths. Experiments 3-6 explored the effect of orthographic uniqueness point in each of the visual fields, as a means of exploring the nature of processing conducted by each hemisphere. Across three experiments, it was shown that words with a late uniqueness point were recognised faster and more accurately than words with an early uniqueness point. This facilitation for late uniqueness point words was evident in the ERP response at 170ms. Furthermore, orthographic uniqueness point was shown to differentially affect each of the hemispheres. Experiments 6-9 provided evidence to suggest that the interaction of length and visual field was influenced by orthographic depth, a property of language that reflects the transparency with which sounds are represented in print. In Chapter Ten, the effect of format distortion on the interaction of length and visual field was explored. Finally, Chapter Ten summarises and discuss the key findings of the present thesis in light of theories that seek to account for lateralised word recognition.

Declarations and Statements

Declaration

This work has not been previously accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed:

Date: 13.07.12

Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Statement 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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Publications, Presentations and Posters

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Wright, V & Izura, C (2008) Word length, frequency and orthographic neighbourhood effects in the right and left visual fields of literate and illiterate participants *Poster presented to the Word Learning Conference, University of York, York, UK*

Tables and Figures

Chapter 1: General Overview

1.1 Introduction

Our visual world is split in two. Due to the neuroanatomy of the human visual system, when our gaze is fixed on a central point in space, words, faces and objects falling to the left of that point are said to be in the left visual field, whilst those falling to the right of centre are said to be in the right visual field. Due to the partial crossing of the optic fibres at the optic chiasm, objects falling in the LVF initially project to the right cerebral hemisphere and those on the RVF to the left hemisphere. The consequence of this splitting of the visual environment on the recognition of printed words is the topic of this thesis.

This thesis focuses on hemispheric asymmetries in visual word recognition. In particular, it concerns itself with a phenomenon known as the right visual field advantage (see Ellis, 2004, for a review), which can be broadly defined as the superior performance of the left hemisphere (in comparison to the right) in the perception of written words. To date, our understanding of the RVFA has relied largely on evidence from behavioural studies that present laterally-displaced words to the left or to the right of fixation. The manner in which these studies measure the RVFA varies substantially but a commonly-employed method involves presenting words of different lengths to each of the visual fields (e.g. Bruyer & Janlin, 1989; Bub & Lewine, 1988; Chiarello, Maxfield, Richards, & Kahan, 1995; Ellis & Young, 1985; Ellis, Young & Anderson, 1988; Eng and Hellige, 1994; Eviatar & Zaidel, 1991). Typically, these studies show a pattern in which increasing word length differentially affects the two hemispheres, with the RH being more strongly affected by word length than the LH.

Such studies draw strong conclusions about how each of the hemispheres performs during word recognition. However, to date, no study has directly measured the electrophysiological activity of the hemispheres in response to increasing word length. This is particularly surprising as a) there is a wealth of research using Event-Related Potentials (ERPs) to explore other aspects of visual word recognition and b) the ERP technique has several attributes (such as a high degree of temporal sensitivity) that mean it is particularly suited to such a task.

This thesis presents a series of experiments designed to investigate the electrophysiological and behavioural effects of increasing word length on each of the cerebral hemispheres. The majority of the experiments used a lateralised lexical decision task – in combination with words and non-words of different lengths - to assess reaction times and response accuracy to stimuli presented in each of the visual fields. In addition, Experiments 1, 2, 3, 8 and 9 also use ERPs as a means of exploring on-line processing in each of the hemispheres.

1.1.1 Thesis overview

Chapter 2 provides the background for the experimental work. In Chapter 2, the literature on lateralised word recognition and hemispheric processing of printed words is reviewed. Relevant terminology, models and concepts are introduced. The chapter focuses on the asymmetric effect of increasing word length, with reference to existing empirical evidence and evaluates the claims that have been made on the basis of this evidence. Chapter 3 introduces ERPs and focuses on how they can be used to explore the processing of visually-presented words in the two hemispheres. ERP components pertinent to the study of visually-presented will also be briefly reviewed. Consideration is also made of the strengths and limitations of using ERPs to investigate cognitive processing. Finally, Chapter 3 also introduces the divided visual field task and outlines some of the conditions and constraints under which the task must be conducted in order to obtain reliable results.

Chapters 4-9 comprise the experimental work and form the main body of the thesis. Chapter 4 describes an experiment that investigated the effect of string length on centrally-presented words and non-words. Behavioural and electrophysiological measures were taken. The results demonstrate an impact of word length in terms of reaction time; ERPs suggested that the effect of length changed across time and hemisphere. Chapter 5 replicates Chapter 4 using lateralised presentation. Behaviourally, the typical interaction of length and visual field was observed for words. This interaction was evident in the ERP analysis at 170ms.

Chapter 6 presents the results of three experiments that explored the effect of *orthographic uniqueness point* (OUP) on lateralised word recognition. The results of the first of these experiments showed that words with a late OUP were recognised faster and more accurately than words with an early OUP. The ERP analysis showed that at 170ms, the hemispheres were differentially affected by OUP. In the LH, early and late OUP words differed in terms of the time they achieved maximum activity; in the RH, voltages were unaffected by OUP. The second experiment in Chapter 6 replicates the first using lateralised presentation. Results showed that, in the RVF, responses to late OUP words were faster than those to early OUP words. In the LVF, length exerted a larger effect than OUP. The third experiment in Chapter 6 replicated the second using a word naming task. The results agreed with those from the second experiment.

Chapter 7 presents two experiments that explored the role of *orthographic depth* and reading direction on the recognition of laterally-presented words. Experiment 7 used Welsh/English bilinguals (who rated their dominant language as English) and native English-speakers as participants. Results showed that bilinguals demonstrated an interaction of length and visual field for English but not Welsh. For English words, the pattern did not differ by linguality. A second experiment explored whether the results of the previous experiments were specifically due to the orthographic depth of Welsh or to the pattern of language dominance demonstrated by the Welsh bilinguals (i.e. their dominant language being orthographically deep and their second language being orthographically shallow). Experiment 6 explored the role of orthographic depth and reading direction. Native Hebrew speakers performed lexical decision on two forms of written Hebrew – pointed (orthographically shallow) and unpointed (orthographically deep).

Chapter 8 presents the results of two experiments that sought to explore the length by visual field interaction in groups of Spanish/English bilinguals. In Experiment 8, it was shown that Spanish/English bilinguals demonstrated a length by visual field interaction for English but not Spanish. Experiment 8 also demonstrated an unexpected finding, in that, contrary to prediction, Spanish/English bilinguals were faster and more accurate in their L2 (English) than their L1 (Spanish). To follow this up, Experiment 9 set out to establish the effect of word length in Spanish and English for centrally-presented words. Results reflected those of Experiment 8 – bilinguals were faster and more accurate in their responses to L2 targets than to L1 targets.

Chapter 9 presents the results of two experiments that explored the effect of non-standard visual format on the recognition of printed words. Visual format was manipulated by rotating words 90° clockwise or by presenting words vertically. Results showed that both hemispheres were equally affected by format distortion, with rotated words being identified faster and more accurately than vertically-presented words. Priming of the first/last letter of a subsequent target speeded response latencies but did not affect global accuracy. Priming assisted both hemispheres but generated a larger benefit in the LH.

Chapter 10 summarises the main findings from the experimental chapters. The implications of the findings for models of word recognition are considered and a new model is proposed to account for the findings of the present thesis.

Chapter 2: The Right Visual Field Advantage

2.1 Introduction

The skilled reader likely experiences the comprehension of written language as an effortless and automatic enterprise. A printed word which has been centrally-fixated for just a fraction of a second can be perceived and identified successfully in less than 500ms, and all without conscious effort on the part of the reader (Ellis, 2004). The speed and accuracy of this recognition process is subject to the effect of a range of variables, including, for example, word frequency, imageability and age of acquisition (Stadthagen-Gonzalez & Davis, 2006). This thesis is concerned with two such variables and the manner in which they interact: a word's length and its position within the visual field. Specifically, the present chapter focuses on what the interaction of word length and position reveals about hemispheric processing of words.

This chapter reviews the literature on the right visual field advantage in visual word recognition, with a particular emphasis on work that has manipulated the length of words presented to each of the visual fields. Its purpose is to provide the theoretical background for the experimental work presented later in the thesis. As such, the review presented herein is necessarily selective. The focus of the chapter is on the similarities and differences between the two cerebral hemispheres in terms of how written words of different lengths are recognised and the conclusions that can be drawn about the performance of the hemispheres on the basis of these studies. The chapter will begin with a brief review of how printed words are thought to be recognised and the organisation of the visual system as it pertains to reading. The literature on word length will then be presented, with an emphasis on work that has manipulated the length of words presented in the two visual fields. Models that seek to account for the interaction of length and visual field will also be discussed. The main findings will then be summarised, along with the limitations of the conclusions that can be drawn.

2.2 The recognition of printed words

To successfully read a familiar word, the skilled reader matches a printed word with a corresponding representation in lexical memory, with the ultimate goal of extracting meaning from text. Whilst such a simple description may belie the complexity of the procedures that allow reading to take place, the cognitive system of the skilled adult reader nonetheless becomes so efficient at identifying written words that reading appears both automatic and effortless to the reader. Indeed, the ease with which readers identify printed words is attested to by the fact that the average adult can read continuous prose at a speed of around 250 words per minute (Smith, 2004), despite the mental lexicon containing representations of between thirty and fifty thousand words (Grainger, 2008). Thus, even though the lexicon is vast and may contain words that look, sound or mean the same as a given target, the reading system develops such that an isolated word need only be fixated for just a fraction of a second in order for its representation in the lexicon to be successfully selected (Ellis, 2004).

As such, it would seem that the reading system becomes particularly efficient at rapidly matching a target word to its corresponding representation in the mental lexicon. In order for this to happen, the reading system needs to be able to distinguish between targets in a fine-grained, feature-based manner – for example, consider the difference between *arc* and *are*. At the same time, the system also needs to be relatively insensitive to gross differences in the surface form of the target, such that *arch*, ***ARCH*** and `arch` all converge upon the same target representation (Dehaene, Cohen, Sigman, & Vinckier, 2005). Given these requirements, it is unsurprising that highly specialised neural and cognitive systems are required to subtend the skill of reading. These systems are unlikely to be innate, as a) structural changes to the brain have been only minimal during the last 100,000 years (Tomasello, 2000) and b) the earliest forms of written language are thought to date back around seven thousand years (Yule, 2006). Therefore, it is likely that there is no dedicated brain structure or innate processing module that has specifically evolved to cope with the demands of reading (Ardilla, 2004). Instead, it is proposed that reading represents a special case of object recognition, wherein brain regions that are specialised for a variety of visual tasks become tuned to the perception of written words as a function of time and experience (McCandliss, Cohen, & Dehaene, 2003).

In this way, the skill of reading stands in stark contrast to the acquisition of verbal language, which is a largely spontaneous and self-organised process that develops purely through exposure to speech and appears to require little conscious effort on the part of the individual (Petersson, 2005). This ease of acquisition is thought to reflect an innate ability to process verbal language. By contrast, reading is a relatively late-acquired cognitive skill (Patterson & Lambon-Ralph, 1999) that does not develop until a) many of its underpinning skills (e.g. speech production/comprehension, the ability to make rapid visual discriminations etc) have achieved a high degree of efficiency and b) without extensive input from an experienced reader and many hours of dedicated practice. Clearly, certain aspects of the cognitive system need to become highly attuned to the recognition of printed words for successful reading to occur.

2.3 Models of word recognition

For the skilled reader, successful reading depends to a large extent upon being able to match familiar printed words with their representations in lexical memory, with the ultimate goal being the extraction of meaning from print. This ability alone, however, is not sufficient to ensure readers can pronounce all words they encounter. This is because vocabulary learning is an on-going process that lasts a lifetime. As such, the adult skilled reader regularly encounters novel words. This means that in order to read fluently, a reader also needs to be able to read unfamiliar words and/or non-words. These are lexical items that do not have yet existing representations in the mental lexicon, meaning that they cannot be recognised via a simple matching procedure. Clearly, any model that seeks to account for reading behaviour must include a mechanism (or mechanisms) by which both familiar and novel words can be processed. We now discuss two models of word recognition that seek to account for how skilled readers can read both familiar and novel words.

2.3.1 The Dual Route Model

The Dual Route Cascaded model (DRC; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) is a theoretical model of how words are read aloud that has been computationally implemented.

Despite its name, the DRC model (Coltheart et al., 2001) posits three routes with which visually-presented words can be read aloud: the lexical non-semantic route, the grapheme-phoneme correspondence (GPC) route and the lexical semantic route. As the lexical semantic route is not implemented in the computational instantiation of the model, and as the present thesis it not concerned with the activation of semantic information during the recognition of visually-presented words, discussion will focus on the lexical non-semantic and GPC routes.

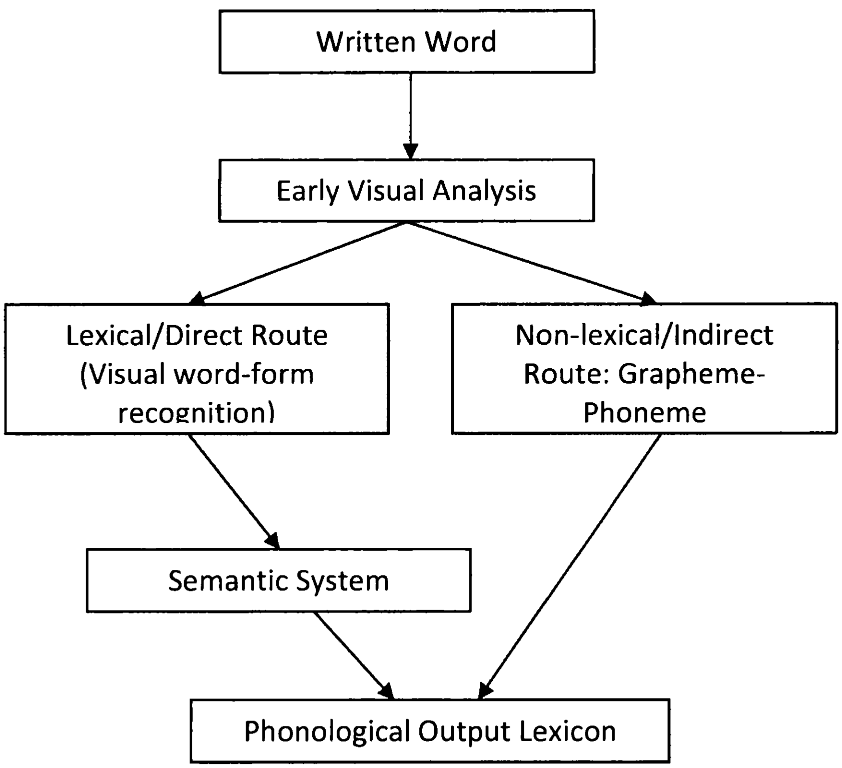


Figure 2.1. A generic dual-route theory of reading aloud (adapted from Jobard et al. (2003)). The figure depicts two of the three possible routes, the lexical non-semantic and GPC route.

2.3.1.1 Lexical non-semantic route

The lexical non-semantic route generates the pronunciation of a word in the following manner: firstly, letter features activate letter units. This happens in parallel, simultaneously across all letter positions. Activations from features to letters are excitatory and there is no feedback from the letter level to the feature level. Letter units then activate the word's entry in the orthographic lexicon. Connections between letter units and the orthographic lexicon are bidirectional and can be either excitatory or inhibitory, allowing for top-down facilitation from the orthographic lexicon to the letter level. The target's entry in the orthographic lexicon then activates the corresponding entry in the phonological lexicon. The target's phonemes are then activated in parallel.

2.3.1.2 Grapheme-phoneme correspondence (GPC) route

The GPC (non-lexical) route achieves pronunciation of a target word by using grapheme-phoneme conversion rules to convert a letter string into a phoneme string. Early analysis of features and letters is as described for the lexical non-semantic route. The GPC converts the first letter of the target into a phoneme and activity cascades forwards to the phonological lexicon. The second letter then becomes active and the GPC now either converts the first two letters into a single phoneme (e.g. *ph*) or into two phonemes and again feeds activation up to the phonological lexicon. This procedure continues until a) activity in the phonological lexicon is sufficient to enable a pronunciation or b) the final letter is reached. Thus, the GPC route proceeds in a serial, letter-by-letter manner.

When a word is presented to a reader, it is assumed that both routes become active simultaneously. Whilst it has been proposed that a 'horserace' model best describes the manner in which the two modes operate, with both routes racing to reach recognition (e.g. Frost, 1998), this suggestion has been rejected by Coltheart et al. (2001). Instead, it may be more appropriate to think about successful word recognition as a dynamically-changing balance between each of the routes, with each contributing towards the ultimate goal of achieving the correct pronunciation of a target word. If this is the case, frequently encountered regular words would bias the balance of the routes such that more input from the lexical non-semantic route was used; for a non-word, the balance may shift such that the GPC route makes a greater contribution to the recognition of the target.

2.3.1.3 Evidence from computational simulations

Coltheart et al. (2001) identified a range of notable effects that commonly arise in behavioural studies of word identification. These included phenomena such as the frequency effect - which is the finding that high frequency words are identified faster than low frequency words (Forster & Chambers, 1973) - and the lexicality effect (i.e. that words are named faster than non-words; McCann & Besner, 1987). In simulations, the DRC was able to reproduce these effects and far out-performed other computational models (such as the PMSP model (Plaut, McClelland, Seidenberg, & Patterson, 1996) and the ZHB model (Zorzi, Houghton, & Butterworth, 1998). The DRC simulations also closely matched human results in terms of their responses to increasing string length of word and non-word targets, with both humans and the DRC demonstrating an effect of length for non-words but not words of between 3 and 6 letters in length.

2.3.2 The Triangle Model (Seidenberg & McClelland (1989) and subsequent versions)

Seidenberg and McClelland (1989; updated by Harm & Seidenberg, 1999) proposed a parallel distributed network model of word recognition and reading (Figure 2.2). The model assumes that when a reader is presented with a written word, three types of codes can be generated: orthographic codes, phonological codes and semantic codes. These codes are activated by means of orthographic, phonological and semantic processing units, with words being represented as the patterns of activity that are distributed across the three types of unit. When a word is read, activity at orthographic units propagates though the network, such that a pattern of activity is generated in phonological units that represent the pronunciation of the target word (Powell, Plaut, & Funnell, 2006).

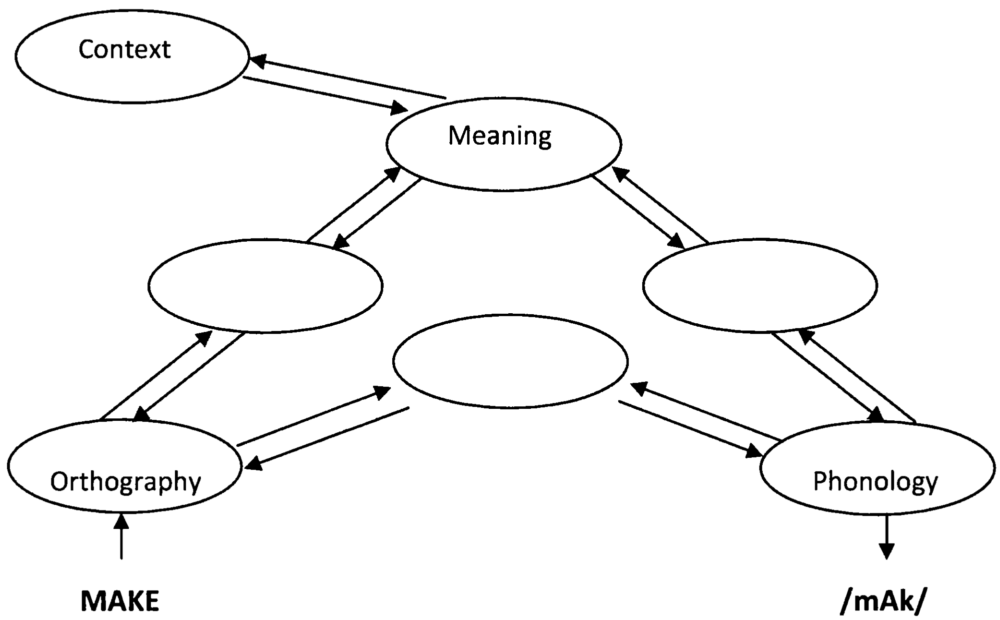


Figure 2.2 The Triangle Model of Reading (Seidenberg & McClelland, 1989)

Like the DRC model, the triangle model posits two routes via which word recognition can occur. However, whereas in the DRC the two routes either map orthography directly to phonology (lexical route) or assemble phonology (non-lexical route), the Triangle model features a pathway that maps orthography directly to phonology and a pathway that maps between orthography and phonology via semantics. The Triangle model also differs from the DRC in terms of how the pathways are utilised. In the DRC, non-words can only be read sub-lexically and irregular words can only be read via the lexical route, with the processing necessitated by each route thought to be qualitatively different from the other. By contrast, in the Triangle model, there is no clear distinction between words of different types (i.e. regular, irregular, non-words) and how they are read. This is because both routes of the Triangle model are thought to rely on a single processing mechanism that is common to both pathways.

Seidenberg and McClelland (1989) implemented a computational version of the direct route from orthography to phonology, using a three-layer connectionist network. The network was trained to generate pronunciations for a large corpus of single-syllable words. Results showed that the network was able to achieve pronunciations of legal words on a par with skilled readers, although reading of non-words was poor in comparison to human readers. Using an updated version of the Seidenberg and McClelland's (1989) model, Plaut, McClelland, Seidenberg, and Patterson (PMSP model; 1996) found that the network read regular and irregular words and non-words equally as well as skilled adult readers, suggesting that the Triangle model is a useful way of modelling human reading performance.

Connectionist models, such as the Triangle model, represent words as distributed patterns of activity across a set of processing units. Links between units are weighted, such that they can become stronger (or weaker) depending on a range of parameters, such as the frequency with which items are presented to the network. As such, one advantage of connectionist models is that they are able to model learning or developmental effects in word reading. This avenue of research has recently been pursued by Monaghan and Ellis (2010), who used variations of Harm and Seidenberg's (1999) computational model to explore developmental effects in language learning. A variation of the model – which the authors term the *developmental model* – was able to successfully demonstrate a range of lexical effects, such as age of acquisition (AoA) and an interaction of AoA and spelling-sound consistency.

Thus, computational models differ from dual-route models in that they propose a single mechanism by which words are read, whereas dual-route models propose two distinct mechanisms. Despite this, both types of model propose that there are two possible ways in which words can be recognised. As such, this thesis assumes a generic dual-route model of word recognition as a framework for conceptualising the way in which printed words are recognised. Whilst it is acknowledged that this is not the only potential explanation, the discrimination between the different models of word reading proposed thus far is beyond the scope of this thesis. Therefore, where necessary, the present thesis will refer to a *lexical* route (in which orthography is mapped directly to phonology) and a *non-lexical* route (in which phonology must be assembled on the basis of grapheme-phoneme conversion rules) in the recognition of written words.

2.3.3 Lexical or non-lexical?

Given that both the lexical and non-lexical routes may operate concurrently – rather than in an either/or manner - the extent to which the activation of each route varies as a function of the psycholinguistic properties of words is of considerable interest. One method that has been employed to gauge the dominant type of processing occurring during the recognition of word and non-word targets is the manipulation of word length. Such a method involves presenting items of different lengths to participants whilst controlling for a range of other psycholinguistic variables that are known to impinge upon response speed and accuracy – for example, word frequency and orthographic neighbourhood size. Dual route models predict that word length affects each of the routes in a different manner. The non-lexical route, which assembles phonology in a serial, letter-by-letter manner, is likely to be highly affected by the number of letters in a target string. By contrast, the lexical route, which allows direct, parallel access from letter units to the orthographic input lexicon, is less likely to be affected by increasing word length. Thus, when other variables are held constant, word length can be predicted to exert a larger effect on non-words (due to a larger reliance on the non-lexical route), whereas increasing string length is less likely to affect responses to familiar words (as processing moves directly from the analysis of letter units to the identification of orthographic word forms).

Thus, when words are matched for a variety of psycholinguistic variables but differ in terms of length, the degree to which words demonstrate a length effect may be a useful indicator of the dominant type of processing (i.e. lexical vs. non-lexical) that is occurring at any particular time.

2.4 Word length effects

Behavioural measures – such as reaction time and accuracy – have been extensively employed in laboratory studies investigating the effect of word length on visual word recognition. For words presented at fixation, a variety of effects of have been noted, with studies reporting both null effects (Fredericksen & Kroll, 1976; Hauk & Pulvermüller, 2004; Juphard, Carbonnel & Valdois, 2004; Richardson, 1976; Weekes, 1997), and inhibitory effects of length (Balota & Chumbley, 1984; Balota, Cortese, Sergent-Marshall, Spieler & Yap, 2004; O'Regan & Jacobs, 1992; Ziegler, Perry, Jacobs and Braun, 2001).

The presence or absence of a length effect may be highly task-dependent. For example, both Fredericksen and Kroll (1976) and Richardson (1976) found length effects in word naming but not lexical decision. In keeping with this, Balota, Cortese, Sergent-Marshall, Spieler and Yap (2004) also identified task-dependent effects, with larger length effects for word naming than for lexical decision. In addition to task-dependent factors, task-specific factors may also influence the effect of word length. The most obvious task-specific factor is the selection of words of different lengths to be used as stimuli. Fredericksen and Kroll (1976) used words of 4 and 6 letters in length and found no length effect for lexical decision. By contrast, Balota, Cortese, Sergent-Marshall, Spieler and Yap (2004) employed words of between 2 and 8 letters and O'Regan and Jacobs (1992) used words of between 4 and 11 letters in length. Both studies identified robust effects of word length.

Another issue related to the selection of words of different lengths for experimental investigation is the extent to which string length is the only variation between word sets. Thus, while some studies control for factors such as number of orthographic neighbours and bigram frequency (Balota et al., 2004), others match sets on the basis of word frequency alone (Fredericksen & Kroll, 1976). Whilst matching for frequency is common in word recognition experiments, the reliability of the frequency databases used to match experimental sets varies between studies. Brysbaert and New (2009) conducted a study looking at a number of traditional and more contemporary frequency norms. They found frequency biases on corpuses that were smaller than 16 million words. Kucera and Francis (1967) is a frequency database based on a corpus of just over one million words. This database has been popular in studies investigating the factors that influence word recognition, letter length among them (Weekes, 1997). The HAL frequency database is, however, based on a corpus of 131 million words and has been the preferred database for other studies looking at word length (Balota et al., 2004). Importantly, Fredericksen and Kroll (1976) another of the studies that found a length effect in word naming, used the Thorndike and Lorge (1944) database based on a corpus of 18 million words. Overall, the evidence suggests that word length effects for centrally-presented words may be highly dependent on task-specific factors.

Recently, New, Ferrand, Pallier and Brysbaert (2006) have suggested that the impact of word length may not be linear and may instead be best described by a U-shaped function, with increasing length facilitating the recognition of very short words (3-5 letters in length), null effects for words between 5 and 8 letters, and inhibitory effects for words between 8 and 13 letters in length. If this is the case, it may be the case that the presence or absence of a length effect is a) not a useful indicator of lexical/non-lexical processing or b) that words of different lengths variably elicit lexical or non-lexical processing, with words between 5- and 8-letters in length being processed lexically and strings >8-letters being processed non-lexically.

2.5 Summary

Dual-route models make clear predictions about the effects of increasing word length. In particular, in the case of familiar words, they predict that words may be processed in a parallel-like manner, meaning that increasing word length results in little or no behavioural effect of length, whilst unfamiliar words and non-words may be processed in a more sequential manner, with increasing string length leading to monotonic increases in reaction time and error rates. Experimental studies that have manipulated word length have reported mixed results, due to differences in task- and stimuli-specific factors. This means it is difficult to gauge the support such studies offer the dual-route model in terms of whether processing of words is lexical or non-lexical. In contrast to centrally-presented words, the results of studies that have presented words of different lengths to the left and right of fixation have yielded more consistent results. Before the results of these studies are considered, we outline the basic structure of the visual system. As will be shown, manipulating the position of words in the visual field can have consequences in terms of which hemisphere initially receives and/or processes a given target.

2.6 Structure of the visual system

It has been proposed that the extent to which each of the two routes of reading contribute to the recognition of printed words varies as a function of the position of the target in a participant's field of view (Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988). Before the reasons for this are outlined, the structure of the visual system as it pertains to reading will be briefly reviewed.

The binocular field of vision – which is defined as the angular extent of the observable world that is visible to a person when they fix their gaze on a point in space – subtends a horizontal angle of almost 180° in humans (Bear, Connors, & Paradiso, 2007). This area of viewable space is commonly referred to as the *visual field* and visual acuity is highest in the central 2-3° of the visual field. Outside this area, visual acuity drops dramatically as distance from fixation increases; thus when attending to stimuli within the visual field, observers tend to orient their eyes and/or head to bring targets into central vision.

The perception of a printed word begins when light reflected from a target enters the eye and forms an image on the *retina*, a light-sensitive tissue that lines the inner surface of the eyeball (see Figure 2.3). The image formed on the retina is inverted due to light passing through the lens at the front of the eye.

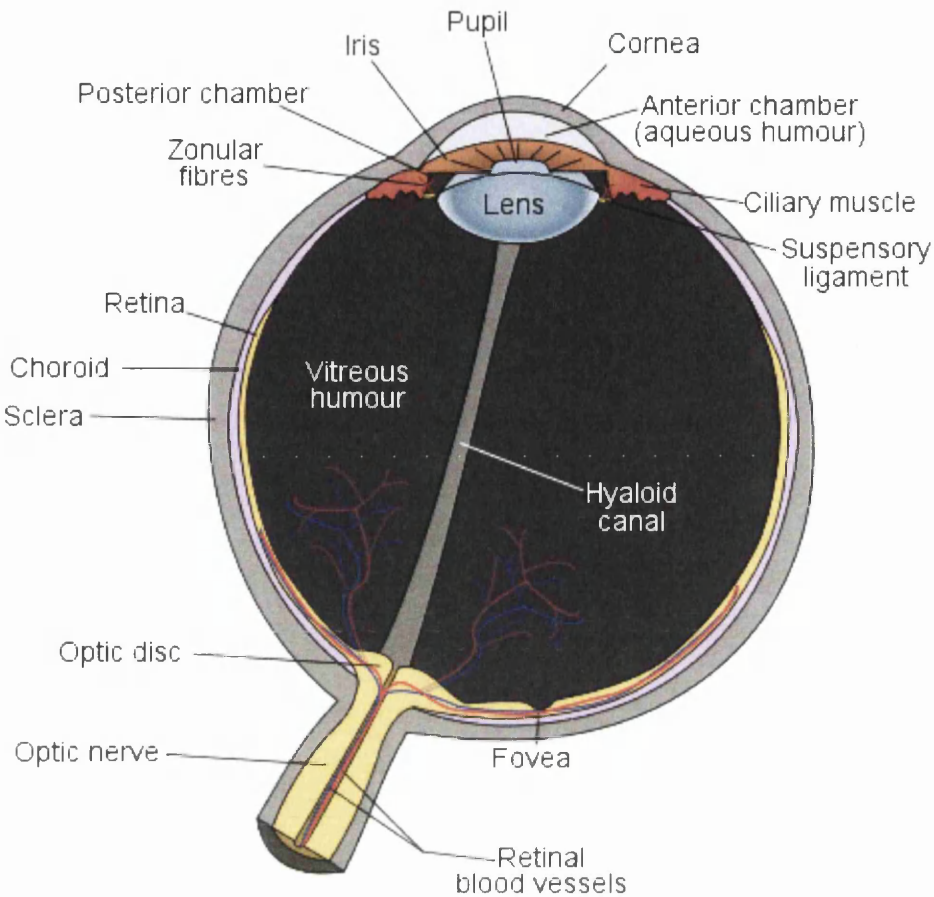


Figure 2.3 The structure of the eye, including the position of the retina and the fovea. Public domain image, not subject to copyright. Retrieved from: http://en.wikipedia.org/wiki/File:Schematic _diagram_of_the_human_eye_en.svg

Although the entire visual field is represented at the retina, visual space is not uniformly sampled. In particular, the central 2-3° of central vision projects its image to an area known as the *fovea*. The fovea contains the largest concentration of cone cells in the eye and is specialised for the high-acuity viewing of objects in central vision (such as might be required for reading or any activity involving fine discrimination of small stimuli). The areas of visual space falling outside the central region map to retinal locations outside the fovea, known as the *parafovea*. The density of photoreceptors is not as concentrated in the parafoveal regions, thus vision there demonstrates less acuity than for foveal regions. Thus, the acuity of vision varies as a function of the density of cells representing the visual field, with small deviations from fixation leading to corresponding drops in acuity as cone density decreases. For example, displacing a target just 1° to the left or right of fixation reduces acuity to about 60% of maximum (Wertheim, 1894). At 2° from fixation, acuity is only around 50% of that for centrally-presented stimuli (Millodot, 1966).

2.6.1 Visual fields

The entire visual field is split vertically through fixation. The visual space falling to the left of fixation is referred to as the *left visual field* (LVF) and the space falling to the right is known as the *right visual field* (RVF). This split is represented at the retinal level, as each eye receives input from both visual fields (Figure 2.4). The retinae themselves are vertically split, such that each has a temporal and a nasal section – these are referred to as hemiretinae. Thus, the LVF is represented by the left temporal hemiretinae and the right nasal retina and the RVF is represented by the left nasal hemiretinae and the right temporal hemiretinae.

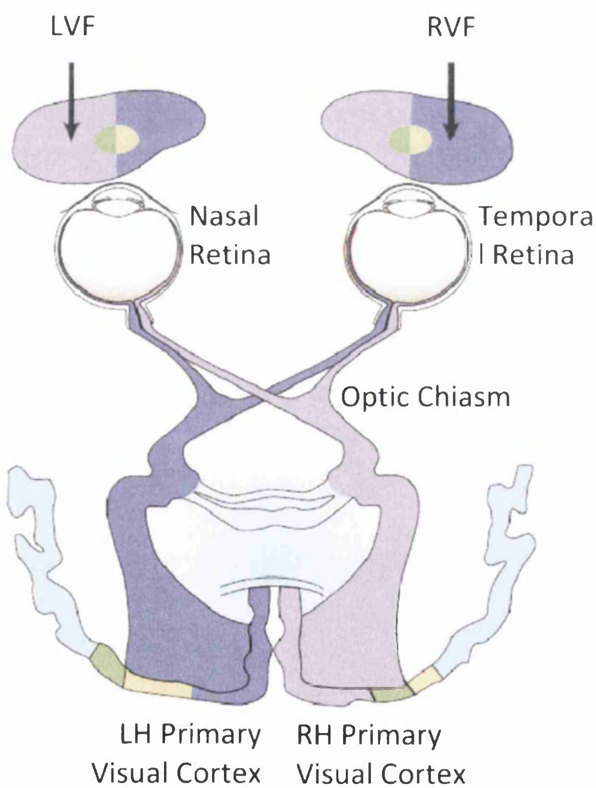


Figure 2.4 Organisation of the human visual system. Note the partial crossing of the optic fibres from the left and right visual fields at the optic chiasm. LVF space initially projects to RH primary visual cortex and vice versa for RVF/LH. Adapted from Lavidor and Walsh (2004)

As Figure 2.4 shows, the optic projections representing the two nasal hemiretinae cross at the optic chiasm. The functional implication of this is that LVF space is initially projected to the primary visual cortex of the right hemisphere, whilst RVF space is projected to the primary visual cortex of the left hemisphere in the first instance. Therefore, in the context of word recognition, a word target presented in the LVF is initially presented to the contralateral hemisphere - in this case the RH - and vice versa for RVF/LH word targets. Although the temporal retinas project to the ipsilateral hemisphere, it has been suggested that the information directed to the ipsilateral hemisphere is of too low a spatial frequency to enable accurate feature discrimination of the kind that is required when reading visually-presented words (Fendrich, Wessinger, & Gazzaniga, 1996).

Some uncertainly exists concerning how the left and right visual fields flank each other, particularly regarding whether the fovea itself is split vertically – with each half projecting to the contralateral hemisphere - or rather is bilaterally represented in each of the hemispheres. Bilateral projection of the fovea has long been assumed, with a strip of between 1-2° thought to be bilaterally represented in the visual cortices (Garey, Dreher, & Robinson, 1991). Evidence in support of this view has largely been drawn from patients exhibiting homonymous hemianopia with macular sparing.

2.6.1.1 Homonymous hemianopia with macular sparing

Homonymous hemianopia is a visual deficit characterised by the loss of either the left or the right visual field in both eyes. Patients with this condition can often demonstrate macular sparing, meaning that vision in the foveal region is unaffected (see Leff, 2004, for a review). If the fovea itself is split, with each half projecting to the contralateral hemisphere, it would be expected that damage causing the loss of the left or right visual field would also cause the loss of the corresponding half of the fovea. That this is not the case in patients with foveal sparing supports the view that the fovea projects to both hemispheres. According to such a view, when unilateral damage occurs, it is assumed that the fovea can still project to the undamaged hemisphere, meaning that the representation of the fovea remains intact (Brysbaert, 1994).

This view has recently been criticised by a number of authors, who have challenged many of the assumptions upon which it is based. Firstly, over a third of patients with homonymous hemianopia do not demonstrate foveal sparing (Lavidor & Walsh, 2004). Secondly, Trauzettel-Klosinski and Reinhard (1998) and Reinhard and Trauzettel-Klosinski (2003) have argued that macular sparing can be accounted for as a consequence of either a) light scattering across the retina that activates photoreceptors on the other side of the vertical meridian or b) preserved functioning of the visual cortex in an otherwise damaged hemisphere. Indeed, Trauzettel-Klosinski and Reinhard (1998) and Reinhard and Trauzettel-Klosinski (2003) have demonstrated that when these two possibilities are excluded, the estimated area of foveal vision that is bilaterally represented ranges from 0° to 0.5°, which equates to about 1.5 letters under normal reading conditions.

2.6.2 Split fovea

Human and primate neuroanatomical studies also lend weight to the argument that the fovea itself is split and not bilaterally represented in visual cortex. Tootell, Switkes, Silverman, and Hamilton (1988) presented visual stimuli to anaesthetised monkeys at an eccentricity of .015° degrees from the vertical meridian. A marker dye was injected into the optic tract such that the visual pathways that were active during the task could be examined post-mortem. The results showed that even when visual stimuli were presented at just .015° from fixation, only pathways to the contralateral hemisphere were marked with the dye. Furthermore, Fendrich, Weesinger, and Gazzaniga (1996) presented a split-brain patient with 2 small shapes presented .25° from fixation. The participant's task was to compare the two shapes. If the fovea was bilaterally represented, the participant should have been able to compare the two shapes and make a same/different judgement. This was not the case.

The results of Tootell et al. (1988) and Fendrich et al. (1996) are thus in agreement with the view that the fovea is not bilaterally represented. However, it is difficult to assess the degree of support these studies offer, as the first was conducted on monkeys and the second on a split-brain patient. Whilst the visual system of the macaque monkey is known to be highly similar to that of humans (Bear, Connors, & Paradiso, 2007), it is nonetheless the case that there might be fundamental differences in the way in which the fovea is represented in monkeys. Furthermore, whilst it is tempting to assume that the functioning of the split brain resembles that of intact brain only with the hemispheres disconnected to some extent, there may be importance differences in the manner in which the split brain and the intact brain visually perceive objects.

Therefore, despite some conflicting findings, at present, the bulk of evidence supports the view that the fovea is not bilaterally represented in primary visual cortex (Lavidor & Walsh, 2004; Leff, 2004). Assuming that this is the case, a visual stimulus – for example, a single word – that straddles the vertical meridian between visual fields may be split such that the left half is projected to the RH and the right half to the LH. Support for this proposition has recently been found both computationally (Shillcock, Ellison, & Monaghan, 2000) and behaviourally (e.g. Ellis, Brooks, & Lavidor, 2005; Lavidor, Ellis, Shillcock, & Bland 2001). As the present thesis is largely concerned with the recognition of laterally-presnted words, an in-depth review of the split fovea model is beyond the scope of the thesis. However, it is noted that Lavdor et al. (2001) demonstrated length effects for centrally-presented words when the bulk of a word's length was in the LVF and an absence of length effects when the variation in length fell in the RVF.

The length by visual field interaction

As outlined above, laterally-presented words initially project to the hemisphere contralateral to the stimulated hemifield. Many studies have taken advantage of the anatomical arrangement of the human visual system to explore the performance of each of the hemispheres during the recognition of visually-presented words. Such studies typically demonstrate a *right visual field advantage* for the recognition of printed words – that is, an advantage for the RVF/LH in terms of response speed and accuracy (see Ellis, 2004 for a review). The reasons for this advantage are not completely understood, although are widely assumed to include the fact that RVF targets enjoy direct connections to the language structures of the LH (an assumption that will be discussed in more depth later). The present section focuses on the effect of word length in each of the visual fields. As such, the aim of this section is to demonstrate that the interaction of length and visual field is a robust phenomenon that has been replicated across a range of experimental tasks and procedures.

2.6.3 Tasks that elicit the length by visual field interaction

Ellis and Young (1985) reported a set of experiments where words and non-words of different lengths were presented to the left and right visual fields. Report accuracy was used as the dependent measure. In Experiment 1, words of 3-6 letters in length were bilaterally presented in the left and right visual fields. A single experimental trial consisted of the simultaneous presentation of two words, one in the LVF and one in the RVF, for 150ms. One of the words was the target to be reported; this was indicated by red lines above and below the word. Results showed that three-letter targets were equally well-reported in both visual fields; however, as string length increased, accuracy remained high in the RVF but declined as a function of string length in the LVF. Thus, visual field and word length interacted, such that increasing length had a larger effect on the LVF than the RVF. This interaction persisted when stimulus presentation was limited to 80ms (Experiment 2). In order to ensure that this effect was not due to the initial letters of RVF words being closer to fixation (and thus more perceptible) than the initial letters of LVF words, the position of the words in each visual field was manipulated such that the initial letters in both visual fields appeared in the same location relative to fixation (Experiment 3). The interaction of length and visual field was preserved even under such conditions. To eliminate physical differences in length between short and long words as a confounding variable, Bruyer and Janlin (1989) presented 4-letter words than have been spaced such that they took up the same physical size as 7-letter words to the visual fields. Again, the interaction of length and visual field was present, demonstrating that the effect was linked to the number of letters in a word and not its physical size. Ellis and Young (1985; Experiment 4) used 5-letter words that consisted of either one or two syllables. The typical right visual field advantage was demonstrated, with no effect of syllable length being evident. Thus, it is likely that the interaction of length and visual field is unaffected by the time taken to pronounce the target, further supporting the idea that it is string length that underpins the effect. Finally, Ellis and Young (1985; Experiment 7) employed non-words as stimuli. A general advantage for the RVF was found; however, in contrast to words, report accuracy was found to decline in both visual fields as a consequence of increasing string length.

One issue with the results of Ellis and Young (1985) is that report accuracy was at near ceiling levels, even under conditions of very brief presentation of words (i.e. 80ms). In order to more fully explore the interaction of length and visual field, Bub and Lewine (1988) and Ellis, Young, and Anderson (1988) both explored the interaction of length and visual field using both RT and response accuracy as dependent variables.

Using a word naming task with unilaterally-presented words, Bub and Lewine (1988) also included a condition wherein words were presented in the central visual field (CVF), allowing comparison of each of the visual fields with centrally-presented words. In terms of RT and accuracy, results from their Experiment 1 demonstrated an effect of length across all locations, with the effect being largest in the LVF and equal in the CVF and RVF. Reaction times were slower in the RVF than the CVF, but, again, the size of the length effect was equivalent in both locations. LVF-presentation yielded RTs that were significantly slower than those of RVF- and CVF-presented targets. This result was replicated in Experiment 4, which used lexical decision as the experimental task.

Ellis, Young, and Anderson (1988; Experiment 1) also reported an interaction of length and visual field for unilaterally-presented targets using lexical decision in terms of both RT and response accuracy, further supporting the results of Ellis and Young (1985) and Bub and Lewine (1988). In their Experiment 4, Ellis, Young, and Anderson (1988) used a semantic decision task with the same word stimuli that had been used in their Experiment 1. The results showed that whilst response latencies to semantic decisions were approximately 75ms slower than those to lexical decisions, the pattern of responding was unaltered; that is, an effect of length was still evident in the LVF but not the RVF.

Also using lexical decision, Iacoboni and Zaidel (1996) presented participants with either unilateral or bilateral targets of 3-6 letters in length. The results showed that unilateral targets generated faster and more accurate responses that bilateral targets. Both target types were pooled together for analysis of length effects, which demonstrated a three-way interaction of length, visual field and lexicality. The pattern of responding for RT and accuracy was such that in the LVF, length effects were evident for both word and non-word targets. In the RVF, an effect of length was evidence for non-word targets only.

Lavidor, Ellis, Shillcock, and Bland (2001) also identified the typical interaction of length and visual field, this time using 5- and 8- letter words presented to the visual fields for lexical decision. Once again, performance in the LVF was slower and less accurate as word length increased whilst the RVF was unaffected by the change in string length.

Not all lexical tasks have demonstrated an interaction of length and visual field, however. Lavidor and Bailey (2005) compared performance on a letter search task and a lexical decision task for 4- and 7-letter words. In the letter search task, target words were presented underneath letter search cues, unilaterally in each of the visual fields. A cue was a string of one letter (e.g. HHHH), and was matched in length to the size of the target. In half of the trials, the cue contained a letter also contained in the target; the other half of cues did not contain a letter also contained in the target. The task of participants was to determine whether the cue letter appeared at any position in the target. Results from the letter search task demonstrated a U-shaped function for both visual fields, with responses to initial and final letters being faster and more accurate than medial letters. However, for lexical decision, the same stimuli generated an interaction of length and visual field, with an effect of length in the LVF but not the RVF.

Thus, word length has been shown to interact with visual field in both uni- and bilateral presentation of stimuli, across a range of tasks, including word naming, lexical decision and semantic decision, for words of between 3- and 8- letters in length. On the basis of these findings, it was proposed that the two hemispheres differ in terms of their responses to written words (Bub & Lewine, 1988; Ellis, Anderson, & Young, 1988). Most notably, Ellis, Anderson, and Young (1988) have suggested that the processing of words in the LH is thought to be relatively insensitive to the effects of word length as the LH is able to map letters in parallel to orthographic word forms. This would mean that extra letter incur little, if any, processing cost in terms of response latency or accuracy. In the RH, where an effect of length is typically observed, it was suggested that this mapping takes place in a more sequential manner.

2.6.4 Reading Direction

Several researchers have assumed that the interaction of length and visual field is a reflection of the LHs dominance for linguistic tasks, with the LH able to recognise words in a parallel-like manner and the RH constrained to a more sequential mode of analysis. An alternative proposition is that the right visual field advantage typically observed in lateralised lexical tasks may reflect the direction in which a script is read. This proposition is more fully discussed in Chapter 7.

2.6.5 Orthographic Neighbourhood Size and Orthographic Uniqueness Point

2.6.5.1 Orthographic Neighbourhood Size

Lavidor and Ellis (2001; 2002) noted that previous studies employing lateralised lexical tasks had failed to control for *orthographic neighbourhood size* (*N*). Orthographic neighbourhood size is defined as the number of words that vary from a target by one letter. Thus, for the target *cat*, orthographic neighbours include *hat, mat, sat, cut, cot, cap, can, cad* etc. Previous studies of word recognition have demonstrated facilitatory effects for larger values of *N* (Andrews, 1997), suggesting that a larger *N* size may benefit processing, possibly due to top-down effects from the word-level to the letter level. To test whether previous studies that explored the interaction of length and visual field were confounded by their lack of control for *N,* Lavidor and Ellis (2001) presented 5-letter words and non-words to each of the visual fields for lexical decision. Half of the words had a small *N* and half had a large *N*. In the LVF, responses to large *N* words were faster than those to low *N* words; in the RVF, *N* did not impact upon RT. No *N* effects were noted in terms of response accuracy. In a follow-up study, Lavidor and Ellis (2002; Experiment 2) presented 5- and 8-letter words to the visual fields for lexical decision. Stimuli were controlled for *N* across lengths. Results showed an effect of length in the LVF but not the RVF in terms of RT. Thus, the interaction of length and visual field persisted once *N* was controlled. Taken together, these results suggest that the RH may be more sensitive to orthographic factors than the LH.

2.6.5.2 Orthographic Uniqueness Point

Thus, it has been shown that *N* differentially affects each of the hemispheres but – when controlled – does not impact upon the interaction of length and visual field. The effect of other orthographic variables on each of the hemispheres is less clear. For example, *orthographic uniqueness point* (OUP) has been shown to impact upon the speed with which centrally-presented words are recognised. The OUP of a word is the letter position at which the target can be uniquely identified from all other possible matches. For example, the OUP for *leisure* is letter position 4 (Kwantes & Mewhort, 1999). Kwantes and Mewhort (1999) presented early and late OUP words to the central-visual field for naming. Responses to early OUP words were significantly faster than to late OUP words. Kwantes and Mewhort (1999) argued that such a finding supported the view that words are processed in a strictly serial, left-to-right manner.

To test the effect of OUP in each of the hemispheres, Lindell, Nicholls, and Castles (2002) and Lindell, Nicholls, Kwantes, and Castles (2005) presented 7-letter early and late OUP words to both visual fields. Using lexical decision, Lindell et al. (2002) found that early OUP words were identified faster than late OUP words in the left and right visual fields for both unilateral and bilateral presentation, suggesting that the manner in which words were recognised did not vary as a function of location. Using word naming speeds as the dependent measure, Lindell et al. (2005) presented 7-letter early and late words to either the left, right or both visual fields. Responses to LVF targets were slower and less accurate than those presented to the RVF or bilaterally to both visual fields; however, there was no effect of OUP in the LVF. In the RVF and when words were bilaterally presented, early OUP words were named faster than late OUP words.

Thus, the effect of OUP in each of the hemispheres remains unresolved. To date, no study has manipulated length, visual field and OUP.

2.6.6 Presentation Format

2.6.6.1 Format distortion

Young and Ellis (1985; Experiment 8) presented participants with laterally-presented words that they subjected to one of two forms of format distortion: vertically-presented words and misaligned words (e.g. $^{h}a_{t}$). Using word report as the dependent measure, Young and Ellis (1985) found the effect of two types of distortion to be the same: although an overall RVF advantage was observed, both types of format distortion induced length effects in the left and right visual fields. Thus, format distortion affected the LH more than the LH, suggesting that the LH advantage in lateralised lexical tasks may only hold so long as words were presented in a standard format. Bub and Lewine (1988) found similar effects using vertically-presented words; comparison of horizontal and vertically presented words revealed a length effect of 30ms, irrespective of orientation. For the RVF, switching from a standard, horizontal format to the unfamiliar vertical orientation doubled the per-letter length effect from 12ms/letter to 24ms/per letter.

Lavidor and Ellis (2001) used *mIxEd CaSe* presentation in order to explore what happens to the interaction of length and visual field under conditions of non-standard presentation. Participants recognised lower, upper or mixed case targets of 4-, 5- or 6-letters in length presented to their visual fields. As with vertical and misaligned words, the mixed case condition induced a length effect in the RVF that was not apparent for either lower or upper case presentation. In the LVF, length effects were observed for all text formats.

Thus, orthographic variables have demonstrated a variety of effects in respect of word length and visual field. However, an examination of the impact of OUP on the interaction of length and visual field would help to further delineate how each of the hemispheres performs during word recognition, as a finding of an effect of early OUP vs. late OUP would suggest that processing is sequential in nature, whilst a null effect would suggest processing is more parallel-like in nature. Furthermore, although gross format distortion – such as mixed case and misaligned text seems to be more detrimental to the LH than the RH, the boundaries of the format distortion which impinge upon the interaction of length and visual field are far from clear.

2.7 Summary

Word length has been shown to exhibit different effects in each of the cerebral hemispheres. This asymmetry has been reported for a range of word lengths (from 3-8 letters), for a variety of tasks (report accuracy, word naming, lexical decision and semantic decision) and manipulating a range of lexical and orthographic variables (*N*, OUP and format distortion). The interaction of length and visual field has been explained most commonly as reflecting an asymmetry in terms of the way in which words are processed in the two hemispheres, with the LH thought to be able to process words in a parallel-like manner, and the RH thought to operate in a more sequential manner. However, this explanation is not universally accepted and several theories have been proposed to explain the interaction of length and visual field. These will now be reviewed.

Before we consider explanations that seek to specifically account for the interaction of length and visual field in visual word recognition, it would be useful to first briefly outline the main ways in which hemispheric asymmetries in general are conceptualised. The aim is not to present an exhaustive review of theories of hemispheric asymmetry; rather, the purpose is to elucidate the ways in which commonly-held theories of asymmetries between the hemispheres may account for the RVF advantage that is typically demonstrated in lateralised lexical tasks.

2.8 General models of hemispheric asymmetries

2.8.1 LH Linguistic/RH visuospatial

There is a generally established view that the RVF advantage stems from the superior capacity of the LH for linguistic tasks (Deason and Marsolek, 2005). This is a view that stems from a body of evidence that demonstrates LH advantages for language-based tasks, and RH superiority for tasks involving other forms of visual perception. For example, the N170 ERP component has been shown to be lateralised to the LH for the recognition of printed words and to the RH for the recognition of faces (see Dien, 2009 for a review). In keeping with this, in the LH, an area in the inferior fusiform gyrus is thought to underpin the recognition of words (references). This area has come to be known as the visual word form area (e.g. McCandliss, Cohen, & Dehaene, 2003). This label, however, is not universally accepted and some authors have argued that the VWFA is not uniquely dedicated to the processing of written words but is also activated by the presence of other visual stimuli (Price & Devlin, 2003). In the RH, the homologue of the VWFA is the fusiform face area (FFA). Activity in this area has been shown to increase in response to the presence of faces (Bentin, McCarthy, Perez, Puce, & Allison, 1996). The relationship between the N170 component and the effect of word length will be explored in Chapters 3 and 4.

The idea that the LH and the RH are specialised for linguistic stimuli and visuospatial processing respectively does not hold up well in general. This is for a number of reasons. Firstly, whilst the role of the RH in the perception of written words remains unclear, there is evidence to suggest RH involvement in some aspects of language perception (e.g. prosody, metaphorical language processing; see Lindell (2006) for a review). Furthermore, evidence from split-brain patients suggests that the RH has some capacity for language, particularly the recognition of isolated printed words (Zaidel, 1978; Zaidel, 1983). Thus, the assumption of a clear dichotomy between the hemispheres in terms of linguistic and visuospatial stimuli is, at best, unwarranted and, at worst, unhelpful in further exploring the functioning of the hemispheres.

2.8.2 LH analytic/RH configural

Bradshaw and Nettleton (1981) argued that the LH is characterised by analytic processing and the RH by configural processing. Thus, Bradshaw and Nettleton suggested that the LH is biased towards a serial analysis of stimuli and the RH towards parallel analysis of stimuli. In respect of the recognition of printed words, according to the analytic/configural view, the LH would be well-suited to handle the serial nature of words (Dien, 2009), with the RH being more suited to the simultaneous analysis of the components of a complex stimulus, e.g., perceiving the components of a face as a whole. The foundation of the analytic/configural view is drawn largely from the face recognition literature, particularly studies that show a face inversion effect (e.g. Bentin et al., 1996). Presenting faces to the visual fields typically elicits a LVF/RH advantage; inverting faces typically affects the RH more than the LH. This finding has been used to suggest the RH processes multi-component objects such as faces as a configural whole, whilst the LH replies on a more serial, top-down strategy (Bentin et al, 1996). However, the literature on the recognition of printed words does not generally support this view, as typically, lexical tasks tend to elicit greater RTs (thought to be commensurate with a serial strategy) in the RH than the LH. Whilst the analytic/configural distinction may be useful for thinking about the way faces and other, non-linguistic complex stimuli are processed, it may be the case that the recognition of printed words is a class of visual object recognition that requires processing that is best dichotomised along other dimensions.

2.9 Accounts of visual field asymmetries in the recognition of printed words

Explanations that have been proposed to account for the interaction of length and visual field typically observed in lateralised lexical tasks will now be reviewed. In general, these models fall into two categories: *callosal relay* models and *direct access* models.

2.9.1 Callosal relay models

The callosal relay model assumes the superiority of the LH for language tasks is such that the RH depends upon the LH for all linguistic processing and that the RH has little – if any – capacity of its own to process written words (Weems & Reggia, 2004). Thus, as words presented to the RH must be transferred to the LH for successful recognition – and because this transfer occurs through the transcallosal fibres of the corpus callosum – such models are referred to as being callosal relay models as linguistic information initially projected to the RH is 'relayed' to the LH for processing. Under such a model, the LH superiority may arise through a number of mechanisms. Firstly, the LH may be able to take advantage of the fact that RVF stimuli enjoy direct access to the language structures of the LH, most notably the posited Visual Word Form Area (Cohen et al, 2000; see Chapter 5 for a more detailed discussion of this work). By contrast, targets presented to the LVF need to be transferred to the LH for recognition. This transfer involves information crossing the corpus callosum. As a consequence of this, the quality of information being transferred may be delayed or degraded en route to the LH. This would result in an effect of length, as, presumably, increasing numbers of letters would take increasingly long to transfer and may be subject to increasing levels of degradation. Furthermore, it may also be the case that information arriving from the RH may not be able to take advantage of the rapid access to orthographic word forms represented by the visual word form area (Iacoboni & Zaidel, 1996).

Callosal relay models are generally supported by neuroimaging findings. For example, in a combined fMRI and ERP task that presented words to the left and to the right of fixation, Cohen et al (2000) found evidence that processing stimuli were initially received in the contralateral hemisphere, before processing became left-lateralised at about 180ms. This is consistent with the view that the LH (possibly the VWFA) is the locus for the recognition of printed words wherever they appear in the visual field. These results were replicated by Cai et al (2008). Similarly, using MEG (magnetoencephalography), Barca, Cornelissen, Simpsons, Urooj, Woods, & Ellis (2010) also observed a similar pattern of LH-centred activity at ~180ms.

Thus, there is some evidence to support callosal relay models and the notion that the RH has little or no capacity for the recognition of written words. However, it is unclear how length effects for LVF targets arise under such models. Transcallosal degradation of information has been proposed (e.g. Ellis, Anderson & Young, 1988) although it is not yet clear the mechanisms by which this degradation would occur and how it would seemingly increase with increasing word length. Furthermore, given that transcallosal delay or lag is thought to be in the region of 6-10ms for right→left transfer (Barnett & Corbalis, 2005), if callosal delay does play a role in the instigation of the length by visual field advantage, it is unlikely to play a large enough role to account for the size of the effect (thought to be around 30ms per letter for LVF stimuli; Ellis, 2004). Therefore, while there is some support for callosal relay models that may account for the facilitated performance of the LH, such models do not completely account for the increasing effect of length observed in the LVF/RH.

2.9.1.1 SERIOL Model

The SERIOL model (Whitney, 2001; Whitney, 2002) is a model of orthographic letter-position encoding. Whilst the precise nature of orthographic encoding is beyond the scope of this thesis, the SERIOL model is outlined here as it has been used to generate testable predictions about visual field asymmetries and has also offered an account of the length by visual field interaction. For the sake of brevity, the SERIOL model will be briefly outlined and discussions of its application will be restricted to those wherein word length was included.

The SERIOL model falls under the general heading of callosal relay models as it is in general agreement with the view that word recognition is essentially a left hemisphere task that is likely modulated by the VWFA. However, the SERIOL model proposes that hemispheric asymmetries in respect of the processing of written words do not reflect hemispheric differences in terms of processing. Rather, Whitney proposes that both hemispheres encode the order of letters in a word in a serial manner, with the hemispheres differing in terms of acuity gradients rather that their independent ability to recognise printed words. In the RVF, the acuity gradient and the locational gradient both drop off in the same direction. By contrast, in the LVF, the situation is reversed and the acuity gradient increases as the locational direction decreases. This leads to increased settling times in the LVF, which account for the general advantage of the RVF. Furthermore, the SERIOL model proposes that length exacerbates the difference between the two gradients in the LVF, meaning that RT necessarily increases as a function of string length even though there is no inherent difference in terms of lexical processing between the hemispheres.

As the SERIOL model proposes that the basis of the LH advantage is based on acuity gradients, a prediction of the model is that adjusting these gradients such that they are optimal should extinguish the RVFA. In order to test this prediction, Whitney and Lavidor (2004) adjusted the contrast of specific letters in the visual fields. Results showed a RVF length effect was established and the LVF length effect was extinguished. As the RVF superiority was eliminated by a simple visual manipulation, Whitney argues that the nature of the hemispheric advantage cannot be due to hemispheric dominance for processing. Further support for the SERIOL model comes from a computational instantiation of the model (Whitney 2001; 2004), with layers that represent the different types of gradients thought to impact upon the word recognition process. Whilst this model makes strong predictions about the manner in which visual field asymmetries arise, it is large untested.

Thus, Whitney has demonstrated that the length by visual field advantage can be reversed using a visual manipulation. Whilst this is an isolated result and would require replication, it nonetheless suggests that there are boundaries to the interaction of length and visual field– and hemispheric processing in general – that have not yet been mapped.

2.9.1.2 Perceptual Processing.

Nazir and colleagues (Nazir, 2000; Nazir et al, 2004) have also proposed a model of visual field asymmetries for the recognition of written words that falls under the category of callosal relay models. They assume that word representations are accessed via the LH VWFA. As such, Nazir and colleagues have argued for a perceptual asymmetry between the visual fields, rather than an asymmetry in terms of lexical processing. Many of the tenets of Nazir's model are based upon findings from the *optimal viewing position effect* (OVP). Studies of eye tracking and reading have shown that optimal recognition of a word occurs when the reader fixates a point that is slightly to the left of centre of the target. Whilst there may be several reasons for this – for example, word beginnings being more informative than word endings (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984) or that the right-ward letter perception span (up 10 characters right of fixation) is known to be larger than the left-ward span (4 letters to the left of fixation; McConkie & Rayner, 1975) – one explanation that has been offered is that splitting the word in this way allows the bulk of the length of the word to be projected to the LH. Thus, over time as a reader becomes fluent, he or she becomes trained to recognise strings of different lengths that fall in the RVF. Thus, perceptual learning plays a role in the length by visual field advantage, as, over time, the reader's retina becomes perceptually trained to identify visually presented words of difference lengths are commonly-occurring retinal locations. However, it should be noted that the OVP effect accounts for the splitting of words that are presented at fixation. It should be noted that the perceptual learning account predicts opposite patterns of effects for languages that are read right→left. Indeed, studies that have examined the position of the OVP in right-left languages have found that the OVP is between the middle of the word and the right-most letter (i.e. the first letter in right-left scripts). However, this reversal of the pattern demonstrated by right-left readers is not always complete (Koriat, 1985). Thus, whilst perceptual training may play a role in the development of the interaction of length and visual field, it is unclear how length effects in the LVF would develop under this model.

2.10 Summary

Thus, callosal relay models all share the assumption that the recognition of visual words occurs in the LH, with very little or no involvement in the RH beyond the relaying of information initially directed to the RH from the LH. Such models have support in the neuroimaging literature; however, some issues remain unresolved. Of most importance to the present thesis is the manner in which a LVF length effect arises. No studies to date have directly tested the callosal relay model in respect of the effect of word length in each of the visual fields. For example, in the study by Cohen et al (2000), although the authors note an initial crossing of responses from the stimulated hemifield to the contralateral hemisphere in terms of the ERP response, later time components analysed activity recorded over the LH in response to written words elicited by presentation to the two visual fields and no direct comparison of the performance of the hemispheres was undertaken.

2.11 Direct access models

The direct access model (Fernandino, Iacoboni, & Zaidel, 2007) assumes each hemisphere is both specialised and independent of the other. Under such a model, poorer LVF performance is not due to the degradation of information as it crosses the corpus callosum; instead, the poorer performance of the LVF is due to the RH being less efficient at carrying out the processing than the LH. Thus, according to direct access models, the hemisphere that received the stimulus (i.e. that which is contralateral to the stimulated hemifield) is the hemisphere that processes the target and initiates the response, with little or no input from the other hemisphere.

2.11.1Two modes of hemispheric processing (Ellis, Young, & Anderson, 1988; Ellis, 2004)

Ellis and Young (1985) and Ellis, Young, and Anderson (1988) proposed that the length by visual field advantage emerged from the different types of lexical processing engaged in each of the hemispheres. In essence, it was suggested that word recognition could operate according to two different modes: the first, Mode A, a parallel-like mechanism that enables rapid parallel-like identification of the letters in a target and the second, Mode B, a more sequential (but not necessarily serial) mode which uses the rules of grapheme-phoneme conversion in order to achieve recognition of a word. The availability of these two modes is thought to differ between the hemispheres. It is suggested that the LH has access to both types of processes, utilising holistic, parallel-like processing for familiar words in standard format and a more sequential-type analysis for unfamiliar words and non-words. By contrast, the RH has access to only the latter type of processing. According to such a model, the interaction of length and visual field arises due to the fact that Mode A processing (the mode of processing used in the LH for familiar words) is less prone to string length, given that letter identity is thought to be processed in a parallel-like manner; consequently, length effects in the RH are assumed to be generated as a consequence of a more sequential encoding of letters, which is necessarily affected by the number of letters in the string. Thus, according to such a model, the LH processes words using Mode A and non-words using Mode B. In contrast, all stimuli presented to the RH, irrespective of their lexicality, are processed using Mode B.

An updated two modes model (Ellis, 2004; Ellis, Ferreira, Cathles-Hagan, Holt, Jarvis, & Barca, 2009) proposes that the source of the length effect in the LVF is unlikely to be the application of grapheme-phoneme conversion rules, given that there is a body of evidence that suggests that the LH (and not the RH) is specialised for this task (e.g. Lambon Ralph & Patterson, 1999). As a consequence of this, the updated model proposes that initial processing is conducted in the contralateral hemispheres but that for LVF targets, abstract letter identities are transferred to the LH, wherein the LH assumed control of recognising the target. Thus, a length effect would arise as the initial computation of abstract letter identities would be inherently length-sensitive. Furthermore, information about letters transferred across the corpus callosum from the RH would not be able to take advantage of the parallel-like access to the visual input lexicon that the LH enjoys for familiar words. Taken in this way, the updated two-modes theory, whilst still positing a role for the RH in the initial extraction of abstract letter identities, could also be accommodated as a callosal relay mode.

2.11.2 Neural sub-systems Model

The neural sub-systems model (Marsolek & Deason, 2005; Marsolek, Kosslyn, & Squire, 1992) suggests that the hemispheres differ in terms of the way in which object features are represented. The model suggests that object recognition relies on two systems – both of which are available in each hemisphere. One of these sub-systems is specialised for the coding of abstract-category exemplars, and the other for specific exemplars. The abstract category sub-system is thought to use feature-based analysis, whilst the specific-exemplar sub-system is thought to use whole-based analysis. Thus, for example, the specific-exemplar sub-system would be sensitive to the difference between *fear* and **FEAR**, whereas the abstract-category sub-system would not; the abstract-category system would be able to process the abstract elements of both stimuli to efficiently converge upon the same representation. By contrast, the specific-exemplar sub-system would process the two targets as different objects, as although both targets converge upon the same lexical entry, the two are visually dissimilar. Marsolek and colleagues have suggested that whilst both sub-systems are available in both hemispheres, the LH relies more on the abstract-category system and the RH relies more on the specific exemplar system. Whilst the neural sub-systems model applies to object recognition in the broadest sense, it is able to thus generate predictions about how words would be processed in each of the hemispheres. However, it is unclear how the model proposes to account for the interaction of length and visual field.

Thus, models that account for the interaction of length and visual field can be summarised into two types: callosal relay models or direct access models. Few studies have directly compared each of the models. In one of the few to do so, Nemrodov et al. (2010) presented Hebrew words and transposed-letter non-words to the left and right visual fields. Results strongly supported the direct access model over the callosal relay model, as contralaterally-presented words and non-words demonstrated evidence of differential processing in each of the hemispheres at 170ms. Furthermore, Weems and Regia (2004) compared computational versions of the callosal relay and direct access models. In addition, they also tested a model that involved a substantial amount of hemispheric co-operation in the recognition of words presented to the two hemispheres. The models were trained on bilaterally-presented three and five letter words, although the effect of word length was not explored as part of the study. Results showed that the callosal relay and cooperative hemispheres models were much less reliant on the RH than the direct access model. However, the study suggested that these two models most closely approximately the performance of human subjects. Whilst, models of this type are vast simplifications of complex processes, they offer a useful way of directly comparing direct access and callosal relay models.

2.12 Aims of the present thesis

A raft of behavioural literature reports a right visual field advantage in the recognition of printed words. In particular, several studies have shown that the effect of word length differs as a function of the position of the word within the visual field, with LVF targets generally being more sensitive to increasing word length than the RVF. Despite being a robust finding in the word recognition literature, the neural basis of this interaction of length and visual field is not well understood. Furthermore, the extent to which processing in each hemisphere is serial or parallel is currently the subject of much debate. As such, the present thesis aims to clarify some of the issues still under debate.

No study to date has used neuroimaging methods to measure hemispheric performance in respect of words of different lengths. Chapters 4, 5 and 9 of the present thesis examined word length effects (Experiments 1 and 9) and the interaction between length and visual field (Experiments 2 and 8) using event-related potentials. Chapter 6 provides behavioural and electrophysiological evidence for the type of processing that underpins word recognition in each of the hemispheres by presenting the results of the first systematic investigation of orthographic uniqueness point and word length in each of the hemispheres. Chapters 7 and 8 investigated the effects of orthographic depth and reading direction on the recognition of laterally-presented words, using speakers of English, Welsh, Hebrew and Spanish. Finally, the effect of format distortion on the recognition of laterally-presented words was explored in Chapter 9. Chapter 10 presents a summary of the experimental work and the implications of the findings for models of word recognition that seek to account for the interaction of length and visual field.

Chapter 3: General Methods

3.1 Event-related potentials

The electroencephalogram (EEG) is a scalp-recorded measure of the brain's electrical activity. In its raw form, the EEG signal is a relatively coarse measure of on-going brain activity, which has both clinical and research applications (Luck, 2005). However, its use in investigating the neural bases of cognitive processing is limited due to the fact that the raw EEG signal represents the activity of many hundreds of different neural sources that are active at any one time, meaning that it is difficult to isolate activity that is generated by a cognitive process of interest.

Derived from the raw EEG signal, the Event-Related Potential (ERP) - a time or phase-locked average of electrical activity recorded across multiple instances of the event of interest - is a useful technique for exploring the neural correlates of cognitive processing. In the present thesis, ERPs are used in experiments featured in Chapters 4, 5, 6 and 7. As such, the present section aims to provide an overview of the ERP technique, along with its potential and limitations in investigating the neural concomitants of cognitive processing. The review will focus particularly on the recognition of visually-presented words. The first part of this chapter describes the neural basis of the ERP signal, the manner in which ERP data are collected and processed, and discusses methods of analyses that enable inferences to be made about cognitive processes in general. The second part of the chapter reviews the literature regarding the use of ERPs in the investigation of visual word recognition.

3.1.1 Neural basis of ERPs

The neuron (Figure 3.1) is the basic functional unit of the nervous system. Neurons are electrically-excitable cells that are highly interconnected, and that both receive and transmit signals to other neurons. These signals – which can be either excitatory or inhibitory in nature – are propagated via chemical and electrical junctions known as synapses.

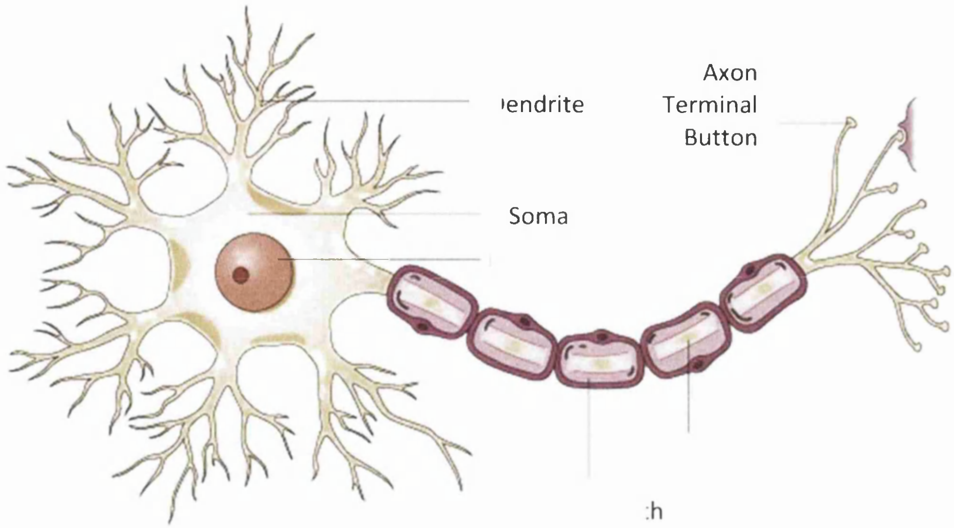


Figure 3.1 Diagram of a neuron

Neurons receive signals from other neurons via their dendrites and transmit signals to other neurons through their axon terminal buttons. When the signal being received from other neurons reaches a threshold level, an *action potential* occurs within the receiving neuron. This triggers a rapid change in the electrical potential of the neuron, causing an impulse to be generated along its axon which is transmitted to other, connected neurons via its synapses.

3.1.1.1 Action potentials

An action potential occurs when the resting state of a neuron is altered. In its resting state, a neuron maintains a negative electrical potential of around 65mV across its membrane (Bear, Connors & Paradiso, 2007). This potential is created by the ionic composition of the intra- and extracellular fluids, with intracellular fluid containing potassium ions [K+] and extracellular fluid containing sodium ions [Na+]. The membrane separating the intra- and extracellular fluids is selectively permeable to these ions, such that when synaptic input from a transmitting neuron exceeds a set threshold, [Na+] channels open, which increases the membrane potential and depolarises the cell, making it more positively charged. If this depolarisation elevates the membrane potential above a critical threshold, an action potential occurs. An action potential consists of a transient change of 100mV in the electrical potential across the cell's membrane that lasts approximately 1ms. This rapid change in the electrical potential of the neuron propagates from the dendrites, along the axon and into the terminal buttons, which synapse with other neurons. Upon reaching the synapse, the action potential causes [Ca2+] ion channels to open, stimulating the release of neurotransmitters from the pre-synaptic cell into the synaptic cleft, where they are taken up by receptors on the post-synaptic cell membranes. If the neurotransmitter released into the synaptic cleft is excitatory, depolarisation occurs and an action potential is generated in the post-synaptic cell. However, if the neurotransmitter is inhibitory, the post-synaptic cell hyperpolarises and an action potential does not occur.

It is unlikely that the electrical activity recorded at the scalp is directly generated by action potentials for a number of reasons. Firstly, activity generated by a single neuron is of such a small magnitude that it is unlikely to be detected at the scalp. Single-cell recordings that directly measure action potentials are possible but rely on invasive, in-vivo techniques (e.g. Allison, Wood, & McCarthy, 1986). Secondly, the duration of an action potential is very brief (~1ms) and given that the temporal resolution of most EEG systems - whilst excellent - is around 2ms, it is likely that such a rapid fluctuation in voltage would not be detected by scalp electrodes that sample activity on a 2ms basis. Thirdly, if two neighbouring neurons are desynchronous – that is, one is depolarised while the other is hyperpolarised - the two potentials will cancel each other out and no net change in potential would be detected (Luck, 2005).

3.1.1.2 Post-synaptic potentials

The opening and closing of ion channels on the post-synaptic membrane causes a change in the electrical potential across the membrane: this change in potential is known as a *post-synaptic potential* and its duration can last from tens to hundreds of milliseconds. The electrical activity recorded at the scalp is likely to be the result of post-synaptic potentials. This is because the duration of post-synaptic potentials is much longer than that of action potentials - thus, there is a higher probability that they will propagate to the scalp. Furthermore, desynchronicity of neighbouring neurons is less of a problem, as a) the duration of a post-synaptic potential means that the activity of neighbouring neurons overlaps to a larger extent, meaning there is a greater likelihood of their activity becoming synchronous and b) the longer duration means increasing numbers of neurons begin to fire as activity spreads. Thus, post-synaptic potentials are likely the source of voltage fluctuation. Nonetheless, scalp-recorded voltages are not the result of the post-synaptic potential of a single pair of neurons; instead, it is likely that neural populations of between 1000 and 10,000 neurons are required for post-synaptic potential activity to be recorded at the surface of the scalp (Luck, 2005).

3.1.2 Factors affecting the propagation of potentials

3.1.2.1 Cell alignment

Several factors determine the extent to which voltages can be recorded at the scalp. In particular, for the post-synaptic potentials of neural populations to propagate to the scalp, the cells must be aligned such that they form an *open field* (Figure 3.2). An open field is formed when, for example, a group of neurons are arranged in parallel, such that when they are active, the action potentials propagate along the axons in the same direction. By contrast, a *closed field* consists of neurons that are arranged such their activity, even when synchronous, is cancelled out.

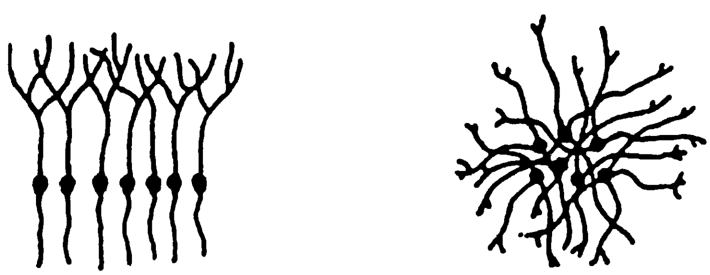


Figure 3.2 Neurons arranged in a) an open field and b) a closed field. Activity in an open field is summative and can propagate to the scalp. Activity in a closed field cancels to zero.

3.1.2.2 Brain anatomy

The likelihood of a potential propagating to the scalp is also dependent upon the location of the source of the potential. For example, neural activity generated by the thalamus and midbrain structures is not amenable to scalp recording as firstly, they are distal to the surface of the scalp and, secondly, they contain neurons arranged in closed fields. Summation of electrical signals to the scalp occurs maximally where neuronal populations are aligned perpendicular to the surface of the cortex, such as is the case with cortical pyramidal cells. However, even cells close to the surface of the cortex may not summate their signal at the scalp. This is due to the folding of the cortex, which can cause closed fields which sum to zero voltage at the scalp. Thus, the size, position and orientation of a given neural population, and whether or not it forms an open or closed field, determine whether its activity is detected at the scalp.

Finally, the shape and conductivity of the brain, skull and scalp also have implications for scalp recordings of electrical activity. The brain itself acts as a volume conductor, propagating the signal outwards from its neuronal generator in all directions. The extent of this spreading is dependent on the position and orientation of a given neuronal population; however, if activity propagates to the scalp, it can typically be detected at several scalp locations. The main consequence of this signal spreading is that, on the basis of scalp-recorded voltage fluctuations, it is not possible to deduce from where in the brain a signal originated. This is often referred to as the *inverse problem*, which reflects the fact that it is mathematically impossible to calculate the neural generator(s) of a scalp-recorded signal, given that it could have been produced by an infinite number of different combinations of generator position, strength and orientation (Helmholtz, 1853). In contrast to this, the *forward problem* – where the size, position and orientation of a neural generator are known – is solvable, and the activity expected to be observed at any point on the scalp can be calculated.

3.1.3 Recording Conventions

3.1.3.1 The Extended International 10-20 System

Skull and brain size vary considerably across participants, which could create difficulties in ensuring that the placement of electrodes is stable across participants. As such, most EEG studies use a standardised system of electrode placement. The Extended International 10-20 System (American Electroencephalographic Society, 1991; Fig 3.3) plots the location of 64 scalp electrodes (plus two reference electrodes). The position of the electrodes is determined in relation to the distance between two skull landmarks, the nasion (the depression just above the bridge of the nose) and the inion (the most prominent ridge of the occipital bone at the rear of the head). Moving clockwise from the nasion to the inion, electrodes are placed at 10° intervals. Similarly, moving from the inion directly to the nasion in a straight line, along the midline of the brain, the distance is once again divided up into 10° increments, with an electrode placed at each. The distances between these electrodes are further subdivided into equal regions and electrodes are placed at each point.

The 10-20 system also assigns location-based names to each electrode, for ease of reference and placement. Brain regions are denoted by letters: Fp = frontal pole, F = frontal, T = temporal, C = central, P = parietal, O = occipital. Where electrodes border two areas, two letters are used, e.g. CP = centro-parietal, PO = parieto-occipital, TP = temporo-parietal. Evenly-numbered electrodes cover the right hemisphere; odd numbers cover the left hemisphere. Electrodes on the midline end with *z* rather than a number.

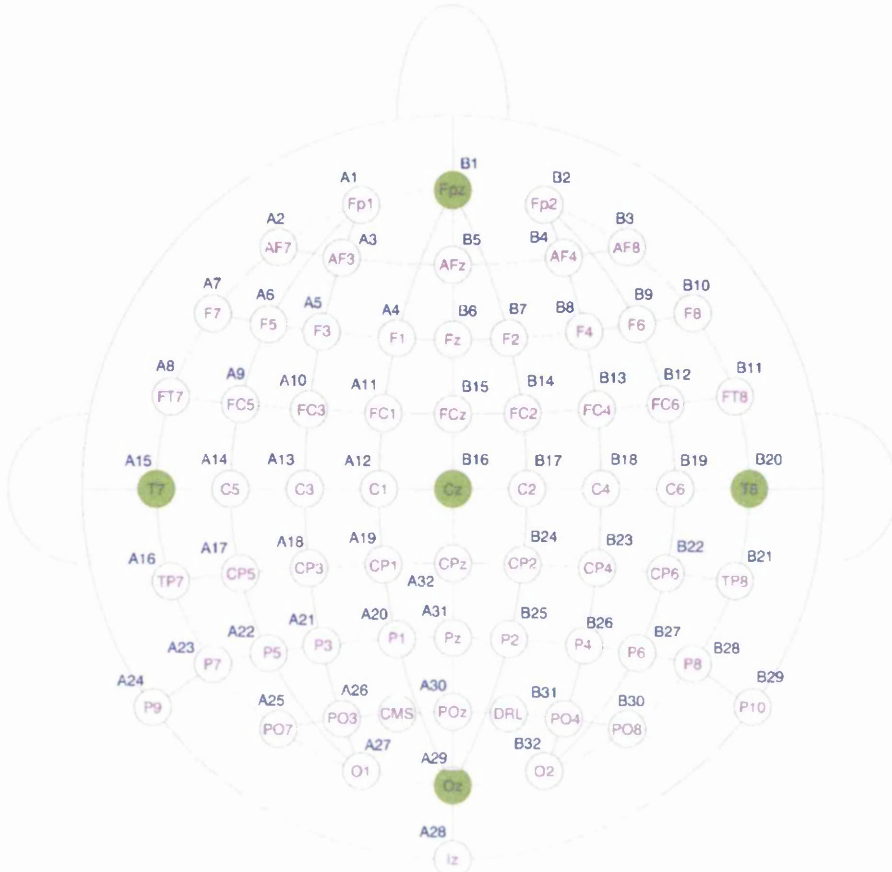


Figure 3.3 Extended International 10-20 System of electrode placement (American Electroencephalographic Society, 1991), showing the position of 64 electrodes plus two reference electrodes, CMS and DRL.

Thus, given the nature of the inverse problem, one limitation of ERPs is that they are a relatively coarse measure of where activity is occurring within the brain. Comparisons of activity across relatively large areas of cortex – such as hemispheric comparisons – are possible and can yield useful data, particularly in respect of hemispheric asymmetries in cognitive processing (Davidson, 1988); however, the localisation of activity on a very fine scale (i.e. in the order of millimetres) is not directly possible. Recently, source localisation procedures have been employed to develop mathematically-based models of the possible generators of a given signal (e.g. Scherg & Berg, 1996). Nonetheless, the spatial resolution of ERPs remains weak, particularly in comparison to other neuroimaging methods such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). As such, the usefulness of ERPs in determining where cognitive processing is taking place within the brain is limited. In contrast, given that data can be sampled as frequently as every 2 milliseconds, ERPs are an excellent tool for exploring the time-course of on-line cognitive processing.

3.1.4 Electrodes

3.1.4.1 Reference electrodes

Voltage is a measure of potential difference between any two points. In regards to the recording of ERPs, the voltage recorded by any given electrode on the scalp represents the potential difference between the electrode and a reference electrode. Two reference electrodes are typically used in EEG recordings; a) a ground electrode and b) an active reference electrode, that is placed somewhere on the participant's body where the electrode is unlikely to detect EEG, EMG (muscle) and EKG (heart) activity but is likely to pick up the same external activity as the active electrode. The mastoid, earlobe and tip of the nose are common sites for active reference electrodes.

As the signal detected at any electrode represents a mix of brain activity, muscle activity and external noise generated by the environment, the use of references allows the influence of non-cerebral electrical activity to be minimised. For example, artifactual activity at all three electrodes (i.e. the ground, active reference and recording site) indicates that the activity is not brain-generated. Such artifacts can be automatically removed from the on-going signal, allowing cleaner, more accurate signals to be detected.

The experiments presented in this thesis use the BioSemi Active II Mark 2 system (BioSemi BV, Amsterdam). As such, all experiments use two reference electrodes, CMS (Common Mode Sense) and DRL (Driven Right Leg). For the purposes of recording, all electrodes are referenced to the CMS, meaning that the potential difference recorded at any electrode represents the difference between the electrode in question and the CMS. Offline, electrodes are re-referenced to the average of all electrodes. This is done on the assumption that the sum of potentials across a spherical surface (such as a head) is zero. Given that the coverage of the entire head is incomplete (i.e. there are no electrodes on the face), use of the average reference relies upon a dense enough array of electrodes (typically, >64 channels) in order for the average reference to be accurately computed.

3.1.4.2 Recording Electrodes

A scalp electrode is a small metal disk that is applied to the head with conductive gel or paste. The electrodes used in the present thesis are made of silver coated with silver chloride (also known as Ag/AgCl electrodes). Ag/AgCl electrodes are chosen as they are relatively immune to corrosion caused by their repeated use and cleaning. Corrosion would reduce the conductivity of the electrodes, reducing their ability to detect small signals and increasing the risk of adding noise to recordings. In all the EEG experiments reported in this thesis, electrodes applied to the head are mounted in an elasticated cap. Gel is applied to each electrode, to ensure good contact with the surface of the scalp.

3.1.4.3 Impedance

In order to record the cleanest possible signals, impedance must be minimised. Impedance is a measure of resistance to the flow of current around a circuit and is typically measured in ohms (Ω). In regard to the recording of EEG signals, several factors can increase impedance, including the quality of contact between the electrode and the bare scalp and the presence of hair/hair products. Thus, care must be taken to minimise impedance by asking participants to refrain from using hair conditioners and products prior to participating in an EEG experiment and/or by gently abrading the surface of the scalp to remove scalp oils and dead skin cells. In the present thesis, impedance was kept below 5kΩ

3.1.4.4 Signal Amplification

The application of an electrode forms a circuit between the electrode, the reference electrode and an AD box (which converts the analogue signal to a digital format). The potential difference between an electrode and the reference is typically very small (5-10μv) compared to that of background noise (50-100μv; Kutas & Dales, 1997). Thus, for the signal of interest to be clearly defined against background noise, signal amplification is required. The BioSemi Active II system uses active electrodes - this means that the signal is amplified on the electrode itself, rather than after it has been converted to a digital signal. This is beneficial as the transmission of a signal along a cable (i.e. on its way to the AD box) can pick up interference. Thus, amplification of a signal after it has picked up interference risks amplifying the signal and the interference.

3.1.4.5 Digitisation

Digitisation of the signal converts the raw EEG into a numerical representation of voltage fluctuations. The number of representations that are stored depends on the sampling rate employed. In the experiments presented in this thesis, a sampling rate of 500Hz is used, meaning that the numerical value of the voltages at all 64 electrodes are sampled every 2 milliseconds.

3.1.4.6 Triggers

The voltage changes recorded at the scalp that reflect cognitive processing are typically very small. These small changes in voltage can be difficult to distinguish from background noise in the raw EEG signal. Thus, the purpose of the ERP technique is to maximise the signals of interest whilst minimising extraneous background noise by averaging events across multiple trials of the same type.

For the raw EEG to be converted to ERPs, the experimental program must be able to send trigger codes to the EEG recording computer. These codes are recorded as part of the EEG signal and indicate exactly when certain events take place. For example, the presentation of an experimental stimulus would mean a trigger code is issued to the recording PC. This code would indicate the type of stimulus presented (for example, 1 = word, 2 = non-word). Another trigger would then be sent when the participant makes a response (i.e. presses *word* or *non-word*, in the case of lexical decision). Finally, a third trigger code is sent when the PC running the experimental program determines if the response was correct or not. These trigger codes enable to recording PC to differentiate between trial types and to know which trials to include as part of the ERP (for example, commonly, ERPs are created separately for word and non-words, for correct and incorrect responses etc.).

Most importantly, the use of triggers enables electrical activity to be time-locked to specific events. To obtain ERPs, the raw EEG is segmented into epochs that typically comprise a pre-stimulus interval, the presentation of the stimulus and the post-stimulus interval of interest. In the present thesis, epochs of 1000ms were used, with a 200ms pre-stimulus interval. This pre-stimulus interval is used as a baseline for the activity that was occurring before a stimulus was presented and, as such, averaged activity for this pre-stimulus interval is subtracted from each time-point of the post-stimulus interval, to ensure only activity related to the presentation of a stimulus is reflected in the ERP. For each participant, epochs of the same trial type are then averaged. These per-participant averages are then averaged across all participants, creating a *grand average*, that represents the averaged pattern of responding for all participants for a given trial type. The grand average is a waveform, typically consisting of a series of peaks (positivities) and troughs (negativities). In isolation, the polarity and timing of these peaks and troughs are not in themselves inherently informative – instead, it is in the comparison of these waveforms across conditions that inferences can usefully be made about underlying cognitive processing.

3.1.4.7 Averaging

A number of assumptions underlie the averaging process (Luck, 2005). Firstly, it is assumed that the voltage recorded at any point on the scalp represents the signal of interest plus electrical noise. Secondly, it is assumed that, for any given trial type, the signal of interest remains stable whilst extraneous noise varies randomly. When these two assumptions are met, the averaging process is able to efficiently extract the signal of interest, time-locked to a specific event, whilst eliminating most background noise.

The number of trials submitted for averaging affects the eventual ERP. For an infinite number of trials, background noise would eventually cancel itself out, effectively isolating the signal of interest. Thus, increasing the number of trials per

ERP improves the *signal-to-noise ratio* of the ERP. This ratio increases as the square root of the number of trials, as the signal of interest is unaffected as noise activity moves closer to zero. Therefore, the number of trials forming part of an ERP must be taken into consideration when making inferences about what ERPs reveals about cognitive processing. In the present thesis, a minimum of 25 trials per condition were submitted for averaging.

3.1.4.8 Inter-trial variability

Even when background noise is effectively managed, the signal of interest may not be completely stable across trials or participants. For example, individual performance can fluctuate across the course of an experiment, as participants become fatigued, bored or suffer attention loss. These factors all introduce a degree of variability into the ERP. Furthermore, individual differences between participants can cause large differences in the timing, polarity and topography of ERP waveforms. Therefore, average waveforms may not closely resemble the performance of individual participants. One particular problem is *latency jitter*, which refers to the inter-trial variability in the timing of activity. The effects of *latency jitter* are two-fold: firstly, a peak or trough of interest can be temporally 'smeared', such that its averaged ERP waveform reflects both the earliest onset and the latest offset. Secondly, a result of this smearing is that waveforms become smaller in magnitude as they are stretched in the time-domain. The impact of latency jitter can be attenuated by the use of mean amplitude measures. Analyses of this type focus on the mean amplitude calculated across a give time-window and are thus less sensitive to variations in peak timing.

3.1.4.9 Artefacts

Thus, use of appropriate recording and digitising techniques help to maximising the signal noise ratio and eliminate extraneous, non-cerebral noise. However, some types of noise are non-random and may be specifically related to trials and events of certain types. When this is the case, the averaging procedure will not eliminate such noise and, unless they are handled appropriately, they will form part of the averaged ERP waveform. This would be problematic as the averaged ERP waveform would not only contain the signal of interest but also the noise associated with it, meaning it would be very difficult to draw inferences about the cognitive processing that is occurring at the neural level. The next section will briefly outline two types of artifacts pertinent to the thesis – blinks and lateral eye-movements – and will describe the manner in which they are handled.

3.1.4.10 Ocular Artefacts

Ocular artefacts are common sources of contamination of the EEG signal. The effects of blinks and lateral eye-movements are particularly prominent at frontal electrodes, although their effects can still be detected at posterior electrodes, with the size of the effect diminishing as the distance between the eyes and recording site increases (Lins, Picton, Berg, & Scherg, 1993). Thus, ocular artefacts have the potential to seriously distort the EEG signal and the resulting ERP. As such, the manner in which such artefacts are handled is vital to the extraction of a clean signal that effectively isolates the cognitive processes of interest. The present thesis used BESA Research 5.3 (BESA GmbH, Germany) to process the EEG signals into ERPs. Ocular artefacts were examined using virtual electrooculogram channels, with separate channels for horizontal eye-movements (HEOG) and vertical eye-movements (VEOG). This approach, developed by Berg and Scherg (1991), estimates ocular activity independent of frontal EEG using "characteristic topographies" for each type of ocular activity. The two main causes of ocular artefacts – blinks and lateral eye movements – will now be described.

3.1.4.11 Blinks

Ocular artefacts can contaminate the EEG signal due to the fact that the eye maintains a potential difference between the positively-charged cornea and the negatively-charged retina. When an eye-blink occurs, the eyelid briefly covers the eyeball, reversing the polarity of the cornea. This causes a wave of between 50-100μv in amplitude, with a duration of between 200-500ms. Thus, eye-blinks are relatively large-scale events that are clearly evident even in the raw EEG signal that can cause gross distortion in ERP waveforms. In the present thesis, participants in EEG experiments were instructed to manage their blinks such that they coincided with inter-stimulus intervals. Prior to starting the experiment, participants practiced the task at hand and were trained to blink between trials. Any trials contaminated by blink artefacts were corrected off-line with a blink correction algorithm (BESA GmbH, Germany).

3.1.4.12 Lateral eye-movements

In the divided visual field task (discussed later in this chapter), the movement of the eyes to the left or to the right of fixation during stimulus presentation represents a serious problem for drawing conclusions about which hemisphere is processing a visually-presented word. When central fixation is maintained, the presentation of a word to the left or to the right visual field means that, in the first instance, its representation is projected to the hemisphere contralateral to the stimulated visual field. The consequence of this is that when fixation is not central, words may not be projected to the intended hemisphere.

In the raw EEG signal, a lateral eye movement causes a positive deflection in the direction of the eye movement, such that, for example, a leftward eye movement causes a positivity on the left side of the scalp and a corresponding negativity on the right side. Given that each degree of movement from fixation generates a deflection of around 16μv at electrode locations adjacent to the eyes (Lins et al., 1993), it is possible to identify when the eyes have made a ballistic saccade in the direction of a laterally-presented word. Unlike with blinks – which, whilst causing contamination of the EEG, do not affect where the eyes are presently fixated and can thus be mathematically corrected without distorting the ERP – trials where the eyes moved substantially left or right of fixation must be rejected. This is because even if an algorithm were used to correct the EEG signal for the shift in eye position, for any trial contaminated with a lateral eye movement, it would be impossible to determine to which hemisphere the stimulus was projected. To ensure that all ERPs reported in the present thesis excluded trials during which a lateral eye movement occurred, the selection of trials for averaging was constrained by limiting selection to those trials with HEOG activity of $<10\mu$v during the first 200ms of stimulus presentation.

3.1.4.13 Inferences from ERPs

An ERP consists of a single waveform comprising a series of peaks and troughs. These voltage fluctuations are the result of multiple underlying latent components that summate at the scalp to produce the observable waveform. Thus, a single peak or trough is not necessarily a direct manifestation of a latent component. In order to draw solid inferences about cognitive processing on the basis of ERPs, it is best to focus on components that have previously been well-studied using paradigms that are known to give rise to the effect of interest (Luck, 2005). ERP components are typically named according to their polarity and timing. Thus, the N400 (Kutas & Hillyard, 1980) is a negative-going component (hence, *N*) that peaks at around 400ms post stimulus. In the present thesis, analyses will focus on the P100 and N170 components. The contribution of these components to the understanding of the recognition of visually-presented words is reviewed later in this chapter.

The present thesis employs two ERP measures – mean amplitude and peak latency. Mean amplitude is the average of activity across a given time-window that typically spans the component of interest. Peak latency is a temporal measure of when a peak or trough reaches its maxima or minima. Whilst, individually, mean amplitude or peak latency are not particularly informative about cognitive processing, relative differences between these measures when comparing across trial types allow us to make inferences about the extent to which a given cognitive process may be engaged at any particular point in time. Whilst careful consideration must be made of the influence of latency jitter and differences between conditions in terms of the numbers of averages in the ERP, all things being equal, differences in mean amplitude and peak latency can reveal much about the neural basis of cognitive processing.

3.1.4.14 Statistical analysis

In order for inferences to be drawn about cognitive processing on the basis of ERPs, appropriate means of analyses must be employed. In the present thesis, mean amplitude and peak latency are analysed using Analysis of Variance (ANOVA).

One problem when analysing ERPs is that voltages recorded at neighbouring electrodes tend to be highly correlated. Thus, analysis of ERPs can result in violation of the sphericity principle, one of the fundamental assumptions of the ANOVA model. Violation of sphericity can result in an increased chance of Type I error (i.e. a false positive); however, this can be controlled by applying the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959). As such, all ERP analyses reported in this thesis use the Greenhouse-Geisser correction, as appropriate.

3.1.5 Summary

Event-related potentials represent a non-invasive, direct measure of the neural activity underlying cognitive processing. Whilst other neuroimaging methods – such as fMRI and PET – offer vastly superior spatial precision, the ability of ERPs to track the time-course of cognitive processing at the neural level is virtually unsurpassed. The relationship between scalp-recorded potentials and their neuronal generators is far from clear; however, ERPs can contribute to our understanding of cognitive processing when experimental manipulations focus on well-studied components using paradigms that reliably elicit the effects of interest. The next section will outline the key ERP components that are known to be associated with the processing of visually-presented words.

3.1.5.1 ERPs and visual word recognition

Over the last thirty years, ERPs have been used extensively in the study of language processing. However, to date, few studies have used ERPs to explore the neural processing of individual printed words in each of the hemispheres, and almost none have systematically explored the effects of word length and visual field. The aim of this section is to outline the ERP components that are most closely associated with the recognition of visually-presented words. As such, this review is not an exhaustive analysis of the use of ERPs in word recognition; rather, its aim is to describe components of interest and how they have been used to explore the neural underpinnings of the cognitive processing of visually presented words.

In respect of written language processing in general, the N400 (Kutas & Hillyard, 1980) and P600 (Osterhout & Holcomb, 1992) represent some of the most well-studied ERP components. Both of these components are sensitive to the semantic aspects of language processing; for example, HIllyard and Kutas (1980) found that when presenting sentences such as, "While I was visiting my hometown, I had lunch with several old...", the word *shirts* at the end of the sentence elicited a much larger N400 wave than when the sentence ended with the word *friends.*

Such late components are of limited interest to the present thesis. This is because it is likely that the recognition of a visually-presented word occurs at or about 250ms (Sereno, Rayner, & Posner, 1998). As such, components occurring later in the processing cycle are more likely to reflect post-lexical access processing and are likely not good measures of the speed with which words of different lengths are recognised. Thus, visual word recognition is indexed by ERP components occurring relatively early in the processing cycle. As such, the present thesis concerns itself with the P1/P100 and N1/N170 components.

3.1.5.2 P1 (P100)

The P1 (or P100) component is a positive-going component, peaking at or near 100ms post-stimulus onset, that is largest over lateral occipital sites. Due to the fact that it is elicited by all visual stimuli and is not evoked specifically by words, its use in ERP studies of language processing has been limited. However, in the present thesis the P1 is of methodological interest, due to the fact that when lateralised presentation is employed, P1 latencies have been shown to be faster to contralateral than to ipsilateral presentations (Doyle & Rugg, 1998). As the majority of the ERP experiments in the present thesis use the divided visual field task, the P1 is used as an indicator of the extent to which the intended hemisphere has been successfully stimulated.

3.1.5.3 N1/N170

The N1 is a negative-going component that peaks between 150-200ms post-stimulus onset. It is also frequently referred to as the N170, featuring posterior negativity and anterior positivity at around 170 milliseconds.

The N170 was first reported by Bentin, McCarthy, Perez, Puce, and Allison (1996), who noted that an N170 wave was present over the right hemisphere when participants were presented with faces (as opposed to control stimuli). Recently, a left hemisphere N170 has been reported in response to the presentation of orthographic stimuli (Maurer, Rossion, & McCandliss, 2008). The left-lateralised N170 is one of the focuses of the present thesis.

The more closely a stimulus resembles a letter string – as opposed to a control stimulus such as a car or a checkerboard – the larger the N170 observed over the left hemisphere (Maurer, Rossion, & McCandliss, 2008). McCandliss, Posner, and Givon (1997) demonstrated that N170s to consonant strings were larger than those for legal words, with orthographically legal non-words falling somewhere between the two. However, others have failed to find N170 sensitivity to lexical status (e.g. Wydell, Vuorinen, Helenius, & Salmelin, 2003). These conflicting results may be due to the type of task involved. It has been suggested that lexicality differences on the N170 may only arise under lexical tasks, such as lexical decision, and not under implicit reading (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999).

Some authors have reported language-specific differences between words and non-words in respect of the N170. For German native-speakers, words, non-words and consonant strings alike have been shown to evoke N170s of equivalent sizes (Maurer, Brem, Bucher, & Brandeis, 2005). In English, however, words are more strongly left-lateralised than non-words, as indexed by the size of the N170 (Maurer, Brandeis, & McCandliss, 2005). One key difference between English and German is the consistency of grapheme-phoneme mapping, with German being highly regular and transparent and English being less regular and more opaque. On this basis, Maurer and McCandliss (2008) suggest that the different lateralisation patterns of non-words in the two languages may reflect the extent to which grapheme-phoneme conversion is employed. As German is highly regular, grapheme-phoneme conversion may be the default mode of reading employed by German speakers, whether they read words or non-words. For English speakers, as English is less regular, they may rely less on grapheme-phoneme conversion for legal words and more for non-words. If this is the case, the N170 may be a marker of the mapping of graphemes to phonemes.

On the basis of this finding, it has been proposed that the N170 for words reflects a fast, highly specialised form of visual object perception that develops across time and after extensive training with orthographic stimuli (McCandliss, Cohen, & Dehaene, 2003). If this is the case, it would suggest that people with different levels of language experience – such as children, developing readers or bilinguals – may show different N170 patterns. In keeping with this, Proverbio, Cok and Zani (2002) found that Slovenian/Italian bilinguals demonstrated a LH-lateralised N170 response for their first language (Slovenian) and a more bilateral response in their second language (Italian). This finding supports the idea that the N170 is modulated by perceptual experience with a class of stimuli, as bilinguals were more visually familiar with their first language than their second.

Lastly, like the P1, the N1 component has been shown to be larger and peak faster for contralateral over ipsilateral presentation (Cohen, Dehaene, Naccache, Lehericy, Dehaene–Lambertz, Henaff & Michel, 2000; Doyle & Rugg, 1998). Therefore, in the present thesis, the N1 will also be analysed as a measure of the extent to which the desired hemisphere was successfully stimulated.

3.1.6 Summary

The recognition of visually-presented words occurs within 250ms of stimulus presentation (Sereno, Rayner, & Posner, 1998). As such, early ERP components can reveal the most about the time-course and manner of processing that occurs when a word is presented to a reader. In respect of the present thesis, the P1 and N1 components will enable inferences to be made regarding the success with which hemispheres were stimulated by lateral presentation of words. Furthermore, the N1/N170 may demonstrate hemispheric asymmetries in respect of word and non-word processing, a finding which is reflected in the behavioural literature (e.g. Ellis, Young and Anderson (1988) and Bub and Lewine (1988) both found a left hemisphere advantage for words but not for non-words).

The N170 may be affected by the degree to which a given language relies on grapheme-phoneme conversion; furthermore, for bilingual participants, there may be differences between N170 asymmetries in their first and second languages. Therefore, the question arises of how bilinguals whose languages differ in terms of the ease with which letters map onto sounds may interact with language dominance and/or proficiency. To answer this question, it would be useful to compare bilinguals whose first language was highly regular and whose second language was irregular with a group whose first language was irregular and whose second language was regular. Chapter 7 presents the results of a behavioural experiment in which English/Welsh bilinguals (Welsh being highly regular and orthographically transparent) recognised short and long words presented to the two visual fields. Chapter 8 presents behavioural and ERP results for a group of Spanish/English bilinguals (Spanish being highly regular).

With the exception of Experiment 1 and 8, all the experiments reported in this thesis use the divided visual field (DVF) technique to measure potential hemispheric asymmetries in the processing of written words. The next section outlines the DVF technique and reviews its reliability in respect of assessing hemispheric performance.

3.2 The Divided Visual Field Task

The divided visual field task (DVF) is an experimental paradigm that enables hemispheric performance on cognitive tasks to be measured. In particular, it is has been well-used as a means of determining performance lateralities in respect of the recognition of printed words. Therefore, the purpose of the present chapter is to outline the DVF task and the conditions and constraints under which it must be conducted in order to achieve meaningful results. Consideration will also be made of the potential and limitations of the task in understanding hemispheric differences in the processing of written words.

The DVF task takes advantage of the fact that targets falling in the LVF are initially projected to the right cerebral hemisphere, and vice versa for RVF/LH targets. The reasons for this crossing of responses were outlined in Chapter 2. Thus, the most basic form of DVF task involves presentation of experimental stimuli to the left and to the right of fixation. In practice, however, there are a range of factors that affect the success of the task at stimulating the desired hemisphere. These factors generally fall into two categories: participant-specific factors and paradigm-specific factors. Both types of factors will now be discussed.

3.2.1 Participant-specific factors

3.2.1.1 Handedness

It is widely assumed that the right visual field superiority for language-based tasks is a function of the left hemisphere's dominance for linguistic processing. Clearly, this is only true for participants who demonstrate left hemisphere language dominance. Therefore, the hemispheric dominance of participants is of key interest in DVF studies, as their language dominance may affect the observed pattern of results. Hemispheric dominance for language can be assessed using a range of neuroimaging measures (e.g. fMRI; Hunter & Brysbaert, 2007). However, this can be both costly and time-consuming. Instead, many studies use handedness (particularly right-handedness) as a means of ensuring participants are LH-dominant. Around 96% of right-handers demonstrate LH dominance for language (Pujol, Deus, Losilla, & Capdevila, 1999). For left-handers, the pattern is less clear - 76% show LH dominance, 10% show RH dominance and the remainder show no superiority for either hemisphere.

Thus, one way in which to ensure a reasonably consistent level of LH language dominance among participants is to restrict participation in DVF studies to those who are right-handed. This can be done by simply asking participants which hand they use to write. In the present thesis, participants completed the Edinburgh Handedness Inventory (EHI; Oldfield, 1971), a questionnaire that asks participants to rate their hand preference (if any) across a range of common tasks. The EHI generates a score that ranges from +100 (extreme right-handedness) to -100 (extreme left-handedness). Bourne (2006) has suggested that the EHI is useful for selecting participants who fall at either ends of the scale, although may be less sensitive at discriminating between participants who show intermediate levels of handedness. As such, in the present thesis, participants were selected for testing if their EHI score was equal to or greater than 80, consistent with being strongly right-handed.

3.2.1.2 Position

The position of the participant in relation to the display screen is also of importance. At a distance of 57cm from the screen, one centimetre corresponds to one degree of visual angle. As stimuli were to be presented at least 2° from fixation (as discussed below), they were displaced 2cm to the left or to the right of fixation. For the visual angle to remain constant, it was imperative that participants remained at a constant distance from the display screen. Thus, other than where indicated[1], all participants who took part in the studies reported in this thesis sat 57cm from the display screen. To ensure head position remained stable across trials and participants, a chin rest was used to fix head position. In order to avoid physical discomfort and visual fatigue, participants were given the opportunity to take regular breaks

3.2.1.3 Paradigm-specific factors

Several aspects of the experimental paradigm itself can impact upon the accuracy with which stimuli are projected to the intended hemisphere.

3.2.2 Presentation of stimuli

3.2.2.1 Location

For the purposes of the present thesis, DVF tasks always involved presentation of targets that were displaced such that their inner edge was 2° from fixation. Whilst there is some uncertainty regarding how the foveal area is represented in each of the hemispheres (see Chapter 2 for a discussion of this issue), it is well-established that vision outside of the central 2-3° of vision is represented in the contralateral hemisphere. Thus, in accordance with Bourne (2006), a cautious approach to

[1] Due to the set up of the EEG lab, participants sat at a distance of 60cm from the screen and were not able to use a chin rest. Stimulus displacement from fixation was adjusted to take this into account, such that stimuli were always 2° from fixation.

hemispheric stimulation was adopted, with stimuli presented in areas known to result in stimulation of the contralateral hemisphere.

3.2.2.2 Duration

Lateral saccades take around 200ms to plan and execute (Rayner, Slowiaczek, Clifton, & Bertera, 1983). In DVF tasks, lateral saccades can be a problem, as, when gaze shifts towards a target, the target is then represented in foveal vision. When this happens, it is impossible to know at which hemisphere – if not both – the stimulus was projected. As such, to ensure participants could not make useful saccades towards laterally-presented targets, stimuli were presented for a duration of 180ms.

3.2.2.3 Fixation Control

Whilst brief stimulus duration may deter participants from making lateral saccades, there nonetheless remains the possibility that participants may anticipate the position of the next target in the visual field and make a pre-emptive saccade. In order to ensure that trials on which an anticipatory saccade occurred are rejected, all EEG experiments reported herein measured the size of participants' lateral saccades as part of an eye movement calibration procedure performed after the experimental task had taken place. The measurements taken as part of this task were used to guide the rejection of trials contaminated by lateral movement artefacts.

Laterally-presented targets can only stimulate the contralateral hemisphere provided central fixation is achieved prior to the onset of a target. The ability of participants to maintain central fixation on the basis of instruction alone has been questioned by some authors, who have argued strongly that only eye-tracking methods can ensure central fixation across all trials (e.g. Jordan, Patching, & Milner, 1998; Jordan, Patching, & Thomas, 2003). In a two-alternative forced choice (2AFC) DVF task, where gaze position was monitored by an eye-tracker, Jordan, Patching, and Milner (1998; Experiment 1) found that participants achieved central fixation on just 23% of trials. Moreover, non-central fixations were asymmetrically distributed, such that 28% fell left of fixation and 49% fell to the right of fixation. Of non-central fixation, 90% were less than one degree from fixation.

In their Experiment 2, Jordan et al. (1998) again used the 2AFC task, this time to compare participants' performance in two conditions: 1) a condition where participants maintained fixation on the basis of instructions alone (i.e. identical to Experiment 1) and 2) a condition where stimuli were only presented when the eye tracker indicated that central fixation had been achieved from the one second interval immediately preceding presentation. In contrast to Experiment 1 – which indicated a right-ward skew in fixation distribution - the instruction-only fixation condition in Experiment 2 demonstrated a left-ward skew, indicating a larger spread of fixations to the left of fixation than to the right. Furthermore, comparison of the instruction-only and controlled fixation conditions in Experiment 2 suggested that the pattern of responding did not vary as a consequence of controlled or uncontrolled fixation. Thus, controlling eye movements such that central fixation was assured on 100% of trials did not result in attenuation of the right visual field advantage compared to when fixation was uncontrolled. This seemingly suggests that the typically-observed right visual field advantage is not the result of an artefactual bias in eye movements. Jordan et al. (1998) argue against such an interpretation, on the basis of a third experiment in which very small shifts in fixation (up to +/-0.5° from fixation, equivalent to approximately two letter characters) were shown to modulate the RVF advantage, with the advantage increasing as fixation moved rightwards, towards a RVF target. In contrast, moving fixation to the left eliminated the RVF advantage but did not instigate a LVF advantage. Thus, whilst the results of Jordan et al. (1998)'s Experiments 1 and 2 suggest that stringent fixation controls do not alter the overall size or nature of the RVF advantage, on the basis of their Experiment 3, Jordan et al. (1998) argue that visual field effects may still be contaminated to some extent by very small shifts in fixation.

Contrary to this, Lavidor and Ellis (2003) have argued that small shifts in fixation have little or no impact upon the patterns of responses in DVF tasks. Using a letter-matching task, Lavidor and Ellis (2003) asked participants to judge whether a probe and target were instances of the same letter. Probe-target pairs were either physical matches (i.e. A-A) or abstract matches (A-a) and probes and targets were either presented in the same visual field or in different visual fields. In Experiment 1, probes and targets were presented 2.8° from fixation (i.e. parafoveally); in Experiment 2, they were presented 0.4° from fixation (i.e. foveally). An eye-tracker was used to ensure stimuli were only presented once central fixation had been established. The exact results of the task itself are not of interest to the present chapter; however, comparison of Experiments 1 and 2 demonstrated that whilst foveal presentations were associated with faster and more accurate responses, the overall pattern of responding did not vary, irrespective of distance from fixation. Thus, the results of Lavidor and Ellis (2003) suggest that small shifts in fixation have no substantial effects on DVF tasks. Taken together, the results of Lavidor and Ellis (2003) and Jordan et al. (1998) suggest that overall responding is largely unaffected by whether fixation is stringently controlled by an eye-tracker and that small shifts (i.e <1°) from fixation may not strongly impact upon the RVF advantage. Clearly, methodological differences exist between the studies of Lavidor and Ellis (2003) and Jordan et al. (1998). Lavidor and Ellis (2003) used a DVF letter-matching task, whilst Jordan et al. (1998) used a 2AFC DVF task. Therefore, the nature of the task employed may affect the size or direction of any visual field effects observed. This could have implications for the inferences that are drawn on the basis of such findings. Lexical task-related differences in DVF performance are discussed later in this chapter.

Both Lavidor and Ellis (2003) and Jordan et al. (1998) used eye-tracking measures to ensure central fixation. However, whilst such measures are useful in ensuring participants are centrally-fixated at the onset of a trial, they are not always compatible with EEG recording systems. This is due to the fact that most eye-trackers use a head-rest to keep head position stable, typically with the chin and forehead being in contact with the frame. Such an arrangement can be problematic for making EEG recordings, as the forehead is typically covered with electrodes – this would not be possible if the head was attached to the eye-tracking headrest. Whilst some EEG systems are directly compatible with eye-tracking measures, and some can record eye fixation related potentials (EFRP; Baccino & Manunta, 2005), such measurements are beyond the scope of this thesis. Nonetheless, the issue of fixation is key to the validity of the DVF task and any inferences that are to be drawn from its use. Bourne (2006) and Hunter and Brysbaert (2007) have suggested bilateral presentation of stimuli as a way of reducing anticipatory saccades and improving the likelihood of central fixation prior to target onset. Under such presentation, two stimuli are presented on each trial, with one in each visual field. The target to be reported or responded to is indicated with an arrow that appears at fixation. Thus, the assumption is that as targets appear in both visual fields, anticipatory saccades do not benefit participants as the item to be responded to is determined not by its location but by a centrally-presented indicator.

Whilst this method is no doubt beneficial to ensuring central fixation and minimising anticipatory saccades, it is of limited use in the present thesis. This is because the presentation of stimuli in both visual fields would lead to simultaneous stimulation of both hemispheres. As the present thesis is interested in hemispheric asymmetries in activity generated by individual laterally-presented words, bilateral presentation would mean it is difficult to draw clear conclusions about the neural response of the hemispheres in relation to the presence of a single word. Thus, all experiments reported in this thesis that employ laterally-presented words make use of unilateral presentation. A fixation cross is also used to ensure central fixation is maintained prior to trial onset.

3.2.3 Lexical Task Effects

The DVF task can be combined with a range of lexical tasks to explore hemispheric processing of words. In order to explore the notion that the LH processes familiar letter strings in parallel, whilst the RH uses a more sequential method, Jordan, Patching, and Thomas (2003) used a 2AFC task to probe letter identification accuracy for 4-letter targets presented at a range of eccentricities from fixation. Although performance was better for RVF than for LVF performance, the pattern of errors across the strings was similar, irrespective of visual field. A *u*-shaped function was evident, such that identification for first and last letters was better than for medial letters. These results strongly suggested that whilst the LH may demonstrate an overall superiority for the task, there was no qualitative difference between the performance of each of the hemispheres. Furthermore, the results supported the view that both hemispheres process words in a sequential manner.

Lavidor and Bailey (2005) have challenged this view by suggesting that the pattern of results observed may be highly task dependent. In particular, Lavidor and Bailey (2005) have suggested that the 2AFC is not an appropriate task with which to explore the interaction of length and visual field, as compared to short words, there are relatively few longer words that differ by just one letter. To this end, Lavidor and Bailey manipulated word length in two tasks, a DVF letter search task (akin to the 2AFC employed by Jordan et al. (2003)) and a DVF lexical decision task. The same stimuli were used in both tasks. For the letter search task, response accuracy, whilst higher in the RVF, showed a similar *u*-shaped function across hemispheres, supporting the findings of Jordan et al. (2003) in suggesting that both hemispheres were performing the task in a similar manner. However, comparison of RTs to 4- and 7- letter words demonstrated the previously-observed interaction of length and visual field, with an effect of length in the LVF but not the RVF. The interaction was also present for lexical decision RTs. Thus, taken together, the studies of Lavidor and Bailey (2005) suggest that the effects of serial position reported by Jordan et al (2003) may a) be highly task dependent, with serial-type processing being more likely to be engaged by tasks involving letter-level processing and b) occur independently of the interaction of length and visual field.

The majority of experiments reported in the present thesis use the lexical decision task (Meyer & Schvaneveldt, 1971). In lexical decision, participants make a binary decision as to whether a given target is a legal word or a non-word, with responses indicated by button press. As such, lexical decision latencies represent the time taken for a target to be visually identified *plus* the time taken for the decision process, response programming and execution to occur. Some authors have argued that lexical decision is too sensitive to these post-lexical processes (e.g. Balota & Lorch, 1986) and that word naming is a better measure of the automatic processing of written words (Harley, 2008). In word naming, participants respond by naming a target aloud (or silently, in the case of silent naming).

The choice of lexical decision for the majority of the experiments in the present thesis was made upon the assumption that the naming of a word (i.e. the type of response required in naming) is lateralised to the LH in right-handed participants. In contrast, motor responses (of the kind required to facilitate a button press) are not strongly lateralised to either of the hemispheres (Bourne, 2006). As such, using word naming may introduce a post-lexical, production-level bias in favour of the LH, as the LH is known to be the dominant hemisphere for spoken tasks. The nature of responses necessitated with lexical decision should not introduce an artefactual bias in response generation into the results of the DVF task. Thus, as neither hemisphere is superior for initiating a motor sequence, any hemispheric asymmetries evident should reflect differences in lexical access rather than post-lexical effects.

3.2.4 Summary

The divided visual field method is a useful technique for measuring hemispheric asymmetries in respect of a range of cognitive tasks. In order for the results of DVF tasks to be used to make inferences about how each of the hemispheres performs during visual word recognition, a range of factors - relating to both the participants and the task itself - must be considered. In accordance with the evidence presented in this chapter, all participants who took part in studies presented in the present thesis are right-handed and sat a fixed distance from the display screen with their heads in a head rest (other than where this was not possible due to the constraints of the lab). For lateralised tasks, stimuli are presented at least 2° to the left or right of fixation, in order to ensure projection to the contralateral hemisphere occurs. Eye-position is not directly controlled in any experiment – this is due to the difficulties of integrating ERP recordings with eye-tracking equipment. However, all EEG experiments enabled eye movements to be examined off-line and trials that were contaminated with significant lateral eye movements during the first 200ms of a trial to be rejected from subsequent analyses. Furthermore, the present chapter has presented a line of argument that suggests that small eye movements (<1°) may not substantially affect the behavioural pattern of responding across hemispheres. Lastly, as it has been shown that visual field asymmetries may be task dependent, the lexical decision task will be employed in the present thesis. This is because lexical decision has been well-used in previous DVF studies and is known to elicit reliable interactions of length and visual field, which are of central interest in the present thesis.

The effect of word length is often used as a metric of the kind of processing that is occurring when visually-presented words are recognised, with the presence of a length effect taken to reflect serial-like processing and the lack of length effect thought to reflect a more parallel-like process. However, whilst the interaction of length and visual field is well-established in the word recognition literature, as Chapter 4 will show, the effect of word length for centrally-presented targets is less clear. In particular, few studies have examined the neural concomitants of increasing word length for centrally-presented words. Thus, before the effects of lateral presentation on ERP responses are explored in Chapter 5, Chapter 4 reviews the literature on word length effects for foveal targets and presents the results of an investigation that examines the effect of increasing word length on the ERP response. The results of that study will serve as a useful comparison for later chapters, when the effect of lateral presentation on ERPs is examined, as it will enable comparisons to be made about how the recognition of words differs between foveal and parafoveal vision.

Chapter 4: The neural basis of the word length effect

As noted in Chapter 2, behavioural measures – such as reaction time and accuracy – have been extensively employed in laboratory studies investigating the effect of word length on visual word recognition. For lateralised stimulus presentation, manipulating the length of words presented to the left and right visual fields typically elicits a length by visual field interaction, such that increasing word length has a larger impact upon the right hemisphere than the left (Ellis, 2004). For foveally-presented words, the effect of word length is less clear, with studies reporting both null effects (Fredericksen & Kroll, 1976; Hauk & Pulvermüller, 2004; Juphard, Carbonnel & Valdois, 2004; Richardson, 1976; Weekes, 1997), and inhibitory effects of length (Balota & Chumbley, 1984; Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; O'Regan & Jacobs, 1992; Ziegler, Perry, Jacobs and Braun, 2001). Recently, New, Ferrand, Pallier, and Brysbaert (2006) have suggested that the impact of word length may not be linear and may instead be best described by a U-shaped function, with increasing length facilitating the recognition of very short words (3-5 letters in length), null effects for words between 5 and 8 letters, and inhibitory effects for words between 8 and 13 letters in length.

The presence or absence of a length effect may be highly task-dependent. For example, both Fredericksen and Kroll (1976) and Richardson (1976) found length effects in word naming but not lexical decision. In keeping with this, Balota, Cortese, Sergent-Marshall, Spieler, and Yap (2004) also identified task-dependent effects, with larger length effects for word naming than for lexical decision. In addition to task-dependent factors, task-specific factors may also influence the effect of word length. The most obvious task-specific factor is the selection of words of different lengths to be used as stimuli. Fredericksen and Kroll (1976) used words of 4 and 6 letters in length and found no length effect for lexical decision. By contrast, Balota, Cortese, Sergent-Marshall, Spieler, and Yap (2004) employed words of between 2 and 8 letters and O'Regan and Jacobs (1992) used words of between 4 and 11 letters in length. Both studies identified robust effects of word length.

Overall, the evidence suggests that word length effects for centrally-presented words may be highly dependent on task-specific factors. However, another possibility is that traditional behavioural measures (i.e., RT and accuracy) may not be sensitive enough to detect an effect consistently, particularly when the difference between word lengths is just one or two letters. In regards to the time taken to identify a printed word, reaction time can be considered as either a) a measure of when processing was completed for a given stimulus, or b) as a measure of when processing had progressed to a stage wherein a decision-making threshold (e.g. word/non-word etc) had been reached. Accuracy, furthermore, is a relatively gross measure of the success of the word identification process. As such, behavioural measures are relatively coarse-grained ways of exploring the time course of lexical processing and it may be the case that in order to detect reliable effects, more sensitive measures may need to be employed (Poeppel & Omaki, 2008).

Several authors have employed electrophysiological techniques as a means of examining the effect of word length for centrally-presented words. Using a sentence reading task, Van Petten and Kutas (1990) examined the effect of word length on the ERP response. Using words of between 3 and 8 letters in length, Van Petten and Kutas (1990) identified a time-dependent effect of length, whereby short words produced stronger responses between 150-225ms, with peak effects over posterior sites, and long words produced larger responses between 250-600ms. During this later time-window, only eight-letter words (the longest used) produced a length effect when compared with words of shorter lengths. This supports New, Ferrand, Pallier, and Brysbaert (2006), suggestion that only words of eight or more letters should cause inhibitory effects.

Using a lexical decision task, Hauk and Pulvermüller (2004) also reported time-dependent effects of word length. Between 80-125ms, longer words evoked larger amplitudes than short words but for several latency ranges within the 150-360ms window, the opposite pattern was observed, with short words generating stronger signals. These results conflict with Van Petten and Kutas (1990) to some extent. Whilst both studies identified stronger signals for short words in the time range

150-225ms, Hauk and Pulvermüller (2004) found that short words evoked larger amplitudes for all time-windows >150ms, whereas Van Petten and Kutas (1990) found that long words produced larger responses between 250-600ms. The difference between the results of these two studies may be attributable to the types of task employed (sentence reading vs. lexical decision) or the selection of stimuli. Either way, what both these studies suggest, albeit in different ways, is that the effect of length may change across time. This supports New, Ferrand, Pallier and Brysbaert (2006) suggestion that the effect of length might not represent a linear function. The U-shaped function described by New et al. on the basis of their multiple regression of lexical decision RTs may be represented in the ERP by 'crossing over' or overlapping effects of length, where the effect of word length is not uniform and short and long words may elicit different effects at different points in the processing cycle.

Interestingly, the stimuli used by Hauk and Pulvermüller (2004) ranged in length from 4.1 to 6.2 letters. This represents a relatively small difference in length and, correspondingly, Hauk and Pulvermüller (2004) found no effect of length in their behavioural measures. However, the authors found robust and long-lasting effects of word length in the ERP, which supports the idea that behavioural measures may be relatively insensitive to small differences in word length, whereas ERPs may be more sensitive to the effect of increasing word length.

Finally, also of note is the fact that Hauk and Pulvermüller (2004) found an asymmetric effect of length in each of the hemispheres between 210-260ms, with the difference between short and long words being larger in the LH than the RH. This is of particular importance to the present thesis, as the ability of each of the hemispheres to deal with word length is one of the central areas of interest.

Magnetoencephalography (MEG) is a neuroimaging technique that uses magnetic fields to measure brain activity. It combines the temporal precision of EEG with good spatial resolution and so is a useful tool in exploring the time-course of visual word recognition. Using MEG and a silent word reading paradigm, Assadollahi and Pulvermüller (2003) found that long words evoked larger responses between 60 and

220ms and short words generated larger responses between 370 and 800ms. This cross-over pattern is similar to that observed by Hauk and Pulvermüller (2004), although the timing of the cross-over effect is somewhat different. Hauk and Pulvermüller (2004) found larger responses to long words <150ms and larger responses to short words >150ms. In Assadollahi and Pulvermüller's (2003) MEG study, larger responses to long words were present until 220ms. This difference may be attributable to differing tasks (lexical decision vs. silent word reading) or the neuroimaging technique employed (ERPs vs. MEG).

In another MEG study, Tarkiainen, Helenius, Hansen, Cornelissen, and Salmelin (1999) also found a time-dependent, cross-over effect of word length. In a silent word reading task, brain activity in the occipital lobe increased with increasing word length at around 100ms and persisted until ~200ms. During this time, global field power (GFP) measures demonstrated strong effects of word length in several time ranges. Between 300-340ms, responses were larger to short than long words. Again, this supports the studies of Van Petten and Kutas (1990), Hauk and Pulvermüller (2004), Assadollahi and Pulvermüller (2003) and New, Ferrand, Pallier, and Brysbaert (2006) suggesting that the effect of length may not be linear and may change as a function of time.

Using principal component analysis to determine the importance of a range of psycholinguistic variables on the time-course of visual word recognition, Hauk, Davis, Ford, Pulvermüller, and Marslen-Wilson (2006) confirmed that word length was one of four orthogonal variables - including *n*-gram frequency, lexical frequency and semantic coherence - that were likely to represent distinct processes during word recognition. ERP data concerning these four factors – plus lexicality – were then submitted to a multiple regression analysis. The earliest effects of word length were evident between 90-100ms, with activity in parieto-temporal-occipital areas - thought to be the locus of the word length effect - emerging at 90ms. The nature of this length effect was such that the longer the word, the larger the positivity. At 100ms, source estimation indicated that the effect was right-lateralised, a fact which the authors suggest is in agreement with studies of lateralised presentation of words, which show length effects are largest for words presented in the LVF.

These findings were largely confirmed in a similar regression-based study (Hauk, Pulvermüller, Ford, Marslen-Wilson, and Davis, 2009), where longer strings predicted larger amplitudes at 100ms, with no effect of lexicality. This suggests that at 100ms, the brain is sensitive to string length whilst being insensitive to the difference between words and non-words.

Hauk et al. (2006) and Hauk et al. (2009) were also able to assess the impact of lexicality on ERPs, something which is absent in the other studies reviewed above. Differences between words and non-words emerged at 160ms (Hauk et al, 2006) and 140ms (Hauk et al., 2009) and were evident in regression coefficients being more negative for non-words than for words. In contrast, Sereno and Rayner (2003) suggested a timeline of visual word recognition based on ERP and eye-tracking measures where lexicality effects were present from ~100ms. Using consonant strings (e.g. *fhvr*) and pseudo-words (e.g. *welf*) as non-words, they found that both types of non-words were distinguished from words at 100ms, but not from each other. If this is the case, it would suggest that just after 100ms post-stimulus onset, the brain is already sensitive to the difference between words, which are well-ordered, previously encountered letter strings, and non-words, which can be well-ordered letter strings never before experienced.

This chapter began with the assertion that word length has a greater impact on the RH than the LH (Ellis, 2004). This asymmetry was proposed after examining data from behavioural studies of laterally-presented stimuli. However, electrophysiological findings further support the differential performance of each of the hemispheres when recognising foveally-presented words. One of the most commonly studied ERP components is the N170 (N1). The N170 is a negative-going waveform that peaks between 150-200ms over posterior areas. Although it can be evoked by visual stimuli in general, it is thought that certain types of visual stimuli, such as faces and words, elicit larger N170 components compared to control stimuli (Maurer & McCandliss, 2008). Furthermore, it has been shown that the N170 is right-lateralised in response to faces (e.g. Rossion, Joyce, Cottrell, & Tarr, 2003) and left-lateralised in response to orthographic stimuli (Bentin, Mouchetant-Rostaing, Giard, Echalier, & Pernier, 1999; Maurer, Brandeis, & McCandliss, 2005; Tarkainien, Helenius, Hansen, Cornelissen, & Salmelin, 1999). This is in keeping with the notion that most right-handers show left hemisphere dominance for language (Springer & Deutsch, 1997). Recently, a growing body of research has supported the idea that reading is essentially a left hemisphere task and that, for a word to be recognised, information about it must be channelled into the language structures of the LH (Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, & Hénaff, 2000; Barca, Cornelissen, Simpsons, Urooj, Woods, & Ellis, 2010). Furthermore, it has been suggested that this asymmetric hemispheric performance may be different for words and non-words. Maurer, Brandeis, and McCandliss (2005) found that, in English speakers, words were more strongly left-lateralised than non-words. This suggests that the N170 does not occur simply as a response to orthographic stimuli; rather, it is a specific response to well-ordered, familiar letter strings.

Recently, the N170 component has been linked with the visual word form area (VWFA; MCCandliss, Cohen, & Dehaene, 2003, although see Price & Devlin, 2003). In a combined fMRI and ERP study, Brem, Bucher, Halder, Summers, Dietrich, Martin, and Brandeis (2006) demonstrated than activity in the VWFA was correlated with the N1 ERP response. This suggests that the N1/N170 ERP response may be the electrophysiological marker of visual word form processing. The VWFA is located in the left occipitotemporal sulcus, adjacent to the fusiform gyrus. It responds to orthographic stimuli more than control stimuli (McCandliss et al., 2003) and has several response properties that facilitate rapid, fluent reading. For example, the VWFA can recognise that a, A, *a* and **A** all represent the same letter. As such, the VWFA is thought to be relatively insensitive to variations in case, size and position within the visual field. However, it is unclear whether this insensitivity extends to word length.

The aim of the present study was to examine the effect of word and non-word length on the ERP response to centrally-presented words. Standard behavioural measures were also taken. As the literature reviewed above demonstrates, previous electrophysiological studies that have manipulated word length have either a) used a small variation in word length, b) not examined the effect of non-word length or c) apart from Hauk and Pulvermüller (2004), have not explored hemispheric differences in response to increasing word length. The present study uses a lexical decision task with 4 and 8 letter words and non-words as stimuli. In accordance with New et al. (2006) and Van Petten and Kutas (1990), these string lengths were chosen to maximise the chance of detecting a length effect both behaviourally and electrophysiologically. ERPs were recorded and measures of mean amplitude and peak latency were selected as dependent variables. It is predicted that a behavioural effect of word length will be present for words and non-words since the manipulation of letter length is relatively large and the experimental sets of words were matched in reliable frequency counts. Furthermore, it is predicted that string length will be reflected in the ERP waveform at ~100ms, with long items generating larger responses than short items. If the left hemisphere is specialised for the processing of printed words, N170 responses to words should show an asymmetrical effect, with responses over the LH being larger than those over the RH. An interaction between hemispheres and word length is expected if the N170 activity is sensitive to the number of letters in a word. Finally, if the effect of length is time-dependent, then in keeping with Hauk and Pulvermüller (2004), responses later than 200ms should be larger to short words than to long words.

4.1 Experiment 1

4.1.1 Method

4.1.1.1 Participants

Fourteen monolingual, native English-speaking students (4 male, 10 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 18-30 (mean age: 19) All were rated as strongly right-handed (>80%) by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £15 in return for their participation.

4.1.1.2 Materials

The materials used in this experiment comprised 200 words and 200 orthographically legal non-words. Non-words were generated from the ARC Non-word database (Rastle, Harrington, & Coltheart, 2002). Half of the stimuli were four letters in length and half were eight letters in length. Item lexicality (word/non-word) and string length (short/long) were orthogonally manipulated, leading to four experimental conditions: (1) four-letter words; (2) eight-letter words; (3) four-letter non-words and (4) eight-letter non-words. All items were presented once. Each condition consisted of 100 stimuli. Words were matched for frequency across sets (from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993)) and number of orthographic neighbours (N) within each word length. The negative correlation observed between word length and N (i.e. the shorter the word, the higher the number of orthographic neighbours) rendered the match for N across word lengths impracticable. For this reason N was matched within but not across lengths. Four letter words had a mean N size of 9.84 and eight letter words had on average 0.57 orthographic neighbours.

4.1.1.3 Apparatus and procedure

The experiment began with 40 practice trials (20 words and 20 non-words) different from those used as experimental stimuli but maintaining the same letter lengths (4-letters and 8-letters items). The experimental stimuli were presented once the practice was over. Participants were instructed to decide if the item on the screen was a real or an invented word. Participants were exposed to a total of 400 experimental trials. Stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 17 inches SVGA display. Participants sat at a viewing distance of 57cm from the display screen in a comfortable chair with a headrest. The experiment was programmed and implemented using E-Prime software (Psychology Software Tools, 2007).

All stimuli were presented in lower-case, Arial font, size 14. To minimise flicker, words appeared white against a blue background and were presented in the centre of the screen. The central fixation cross subtended a visual angle of 1°.

Trials were organised into ten randomised blocks of 40 items to allow participants to rest. Item selection for each block was randomised and controlled by the experimental program. At the end of each block, participants could take a break and trials recommenced once the participant pressed one of the keys on the response box. At the end of each block, participants were presented with a screen that explained they could take a break for as long as they like and could recommence trials by pressing a button. Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 150ms in the centre of the screen. The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, a message appeared on the screen for 2000ms, indicating that their response had been recorded. Immediately after that, the next fixation-cross reappeared as the next trial began. The importance of fixating on the cross during the task was emphasised in the experimental instructions, as was the need for speed and accuracy. Participants were also instructed not to blink during trials. During the practice trials, participants were trained in how to time their blinks such that they occurred after experimental trials.

4.1.1.4 ERP Acquisition and Processing

The electroencephalogram (EEG) was recorded in an electrically-shielded EEG chamber housed within the Department of Psychology, Swansea University, UK. Participants sat in a comfortable seat, at a viewing distance of 57cm from the screen, and were instructed to refrain from moving, blinking or making eye movements during experimental trials. Data were recorded from 64 Ag/AgCl electrodes (BioSemi Active II System, BioSemi Systems, Amsterdam, NL) mounted on an electrode cap and arranged according to the extended International 10-20 system. Sampling rate was 500Hz and a 0.1-30Hz bandpass filter was applied. Data were converted off-line to the average reference and analysed using BESA Research 5.3 (BESA GmbH, 2011). Upon completion of the experimental testing session, participants performed an eye movement calibration task for use in eye artifact rejection (Berg & Scherg, 1991).

4.1.1.5 EEG Pre-Processing

The continuous EEG for each participant was divided into epochs of 1000ms in length, beginning 200ms pre-stimulus onset. Trials contaminated with eye artifacts or with peak-to-peak potential differences larger than 75μv in any channel were rejected. All epochs were baseline-corrected over the 200ms pre-stimulus interval and converted to the average reference.

4.1.2 Results

4.1.2.1 Behavioural Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (6.46% of all trials). This led to two participants being excluded from subsequent analyses due to excessive levels of anticipatory responses. Error responses (4.69%) were rejected from subsequent analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 4.1.

Only correct responses were analysed. A repeated-measures ANOVA was conducted on RT data by subjects (F_1), with word length (short vs. long) as a within-subjects factor. A by-items analysis was also conducted (F_2), with word length as a between-subjects factor.

4.1.2.1.1 Responses to words

Short words were recognised faster than long words: $F_1(1,11) = 12.00$, MSe = 10930.06, $p < .005$, $\eta^2_p = .52$; $F_2(1,198) = 6073.58$, MSe = 89052.95, $p < .001$, $\eta^2_p = .10$. Analyses of errors showed no effect of length. Short and long words were responded to with equal levels of accuracy by subjects and by items.

Table 4.1 Mean reaction times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of word length and target lexicality in Experiment 1

	WORDS		
	4 Letter	8 Letter	Difference
M	341	412	71
SD	138	155	
% Acc	96	94	-2
	NON-WORDS		
M	381	433	52
SD	153	183	
%Acc	92	91	-1

4.1.2.1.2 Responses to non-words

Two further ANOVA analyses demonstrated a main effect of non-word length by-items and by-subjects, with short non-words being recognised faster than long non-words: $F_1(1,11) = 8.47$, MSe = 24554.74, $p < .05$, $\eta^2_p = .41$; $F_2(1,198) = 6.54$, MSe = 2395.82, $p < .005$, $\eta^2_p = .37$. Analysis of errors showed that there were no significant differences between short and long non-words.

4.1.2.2 Electrophysiological Results

Only trials with correct responses were included in ERP analyses. Grand average RMS curves (Figure 4.1), plotted for all conditions across all electrodes across time, indicated three prominent peaks in the ERP distribution, at 100ms, 180ms and 300ms post-stimulus onset. These peaks were considered for analysis since they occurred before the participant's average response time (349ms). For each peak, grand average topographies were examined and time-windows of interest were selected as follows: for the peak at 100ms, the maximal positive deflection between 70 and 130 ms (corresponding to the P1 component); for the peak at 180ms, the maximal negative deflection between 130 and 230ms (corresponding to the N170) and for the peak at 300ms, the maximal positive deflection between 240ms and 340ms over occipitotemporal sites. The focus of interest was on electrodes PO3, PO7 and P7 over the left hemisphere and on PO4, PO8 and P8 over the right hemisphere. These sites were selected for analysis on the basis of their reported sensitivity to the orthographic properties of words (Bentin et al, 1999). As the focus of the present study was on hemispheric differences, to maximise the hemispheric comparison, the three electrodes over each hemisphere were analysed as a single group.

ERPs were analysed for mean voltage computed across time windows that spanned the peaks of the components of interest. Peak latencies were also computed and analysed. Thus, three-way repeated-measures ANOVAs were conducted separately on mean voltage and peak latency for the peaks at 100ms, 180ms and 300ms, with hemisphere (left vs. right), lexicality (word vs. non-word) and word length (short vs. long) as within-subjects factors. All pairwise comparisons are reported using the

Bonferroni correction to control for multiple comparisons (all p < .05 unless otherwise stated).

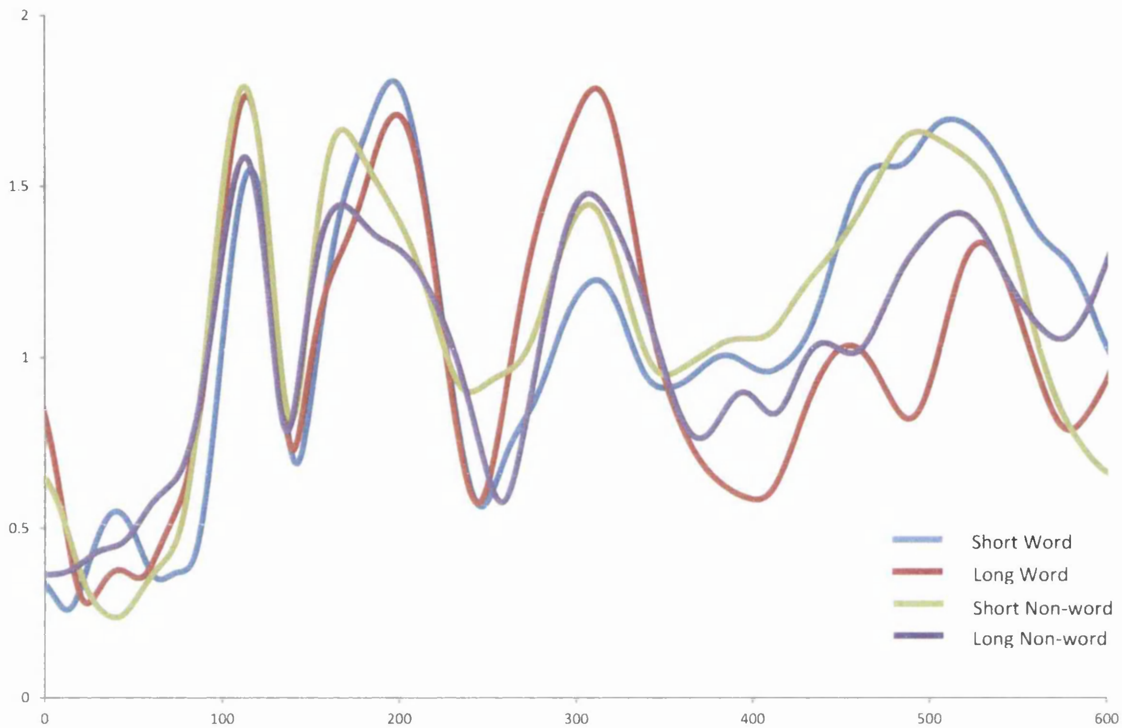


Figure 4.1 Grand average RMS curves for all conditions plotted across all electrode sites over time.

4.1.2.2.1 Event Related Potentials (ERPs)

Figure 4.2 presents grand average ERP curves for contralaterally-presented words and non-words, plotted over the left and right hemispheres. Figure 4.3 presents topographic scalp maps of the rear of the head for all conditions.

4.1.2.2.2 P1 Mean Amplitude and Peak Latency

P1 amplitudes were more positive over the RH (2.57μv) than over the LH (1.55μv): $F(1,11)=7.22$, MSe = 25.17, $p < .005$, $\eta^2_p = .40$. A significant effect of length was also evident: $F(1,11)=11.69$, MSe = 4.60, $p < .01$, $\eta^2_p = .52$, with long words (2.80μv) evoking more positive waveforms than short words (1.84μv). There was no main effect of lexicality [$F(1,11)=4.32$, MSe = 2.13, $p = .06$, $\eta^2_p = .28$], and no interaction of hemisphere and length [$F(1,11)=2.18$, MSe = .311, $p = .17$, $\eta^2_p = .17$], hemisphere and lexicality [$F(1,11)=1.45$, MSe = .73, p = .25, η^2_p = .12] or length and lexicality [$F(1,11)=.20$, MSe = .07, p = .66, η^2_p = .02].

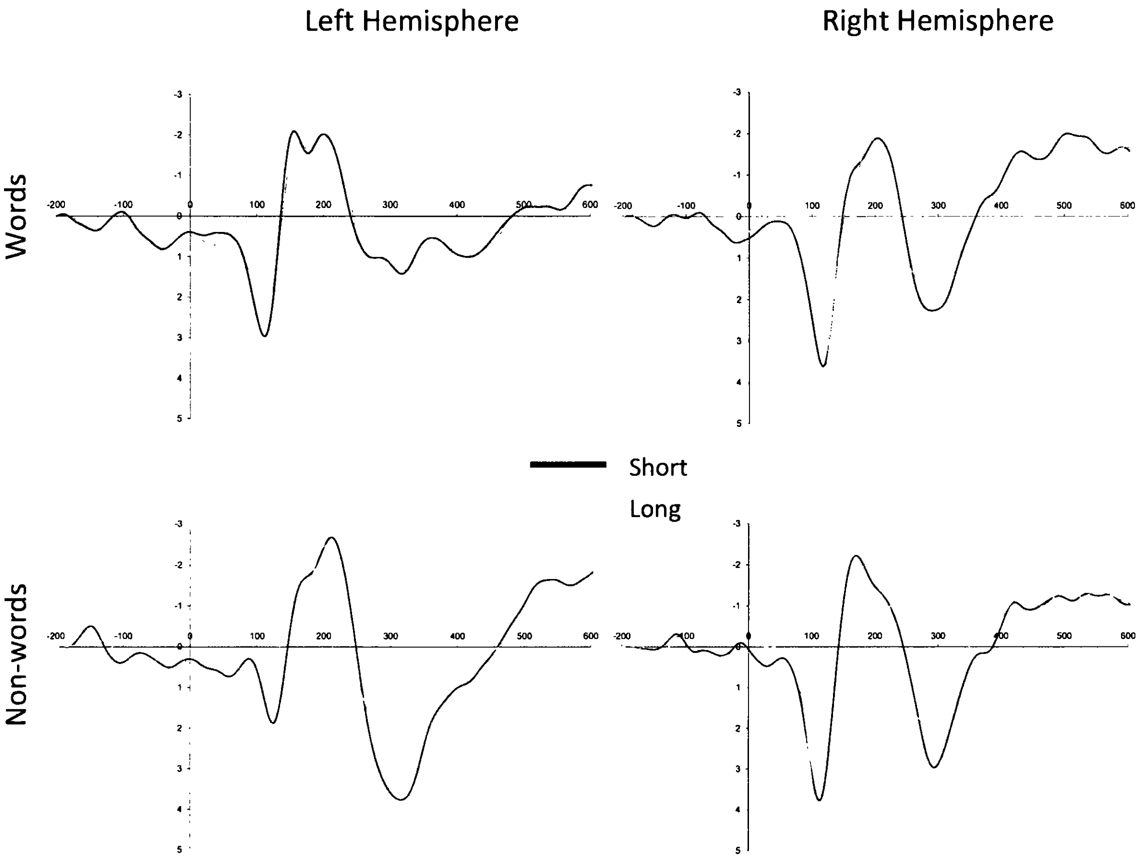


Figure 4.2 Grand average ERP curves for LH/RVF (left panels) and RH/LVF (right panels), for words (top panels) and non-words (bottom panels). *y*-axis is time in milliseconds . *x*-axis is measured in μv. Negative is plotted up.

Lexicality, length and hemisphere interacted [$F(1,11)=5.06$, MSe = 25.17, $p < .05$, η^2_p = .32], demonstrating differential effects for words and non-words in each of the hemispheres. In the LH, there was an effect of length for non-words ($p < .001$) but not for words. In the RH, an effect of length was marginally significant for words ($p < .056$) but not for non-words. No peak latency effects were found at 100ms.

4.1.2.2.3 N170 Mean Amplitude and Peak Latency

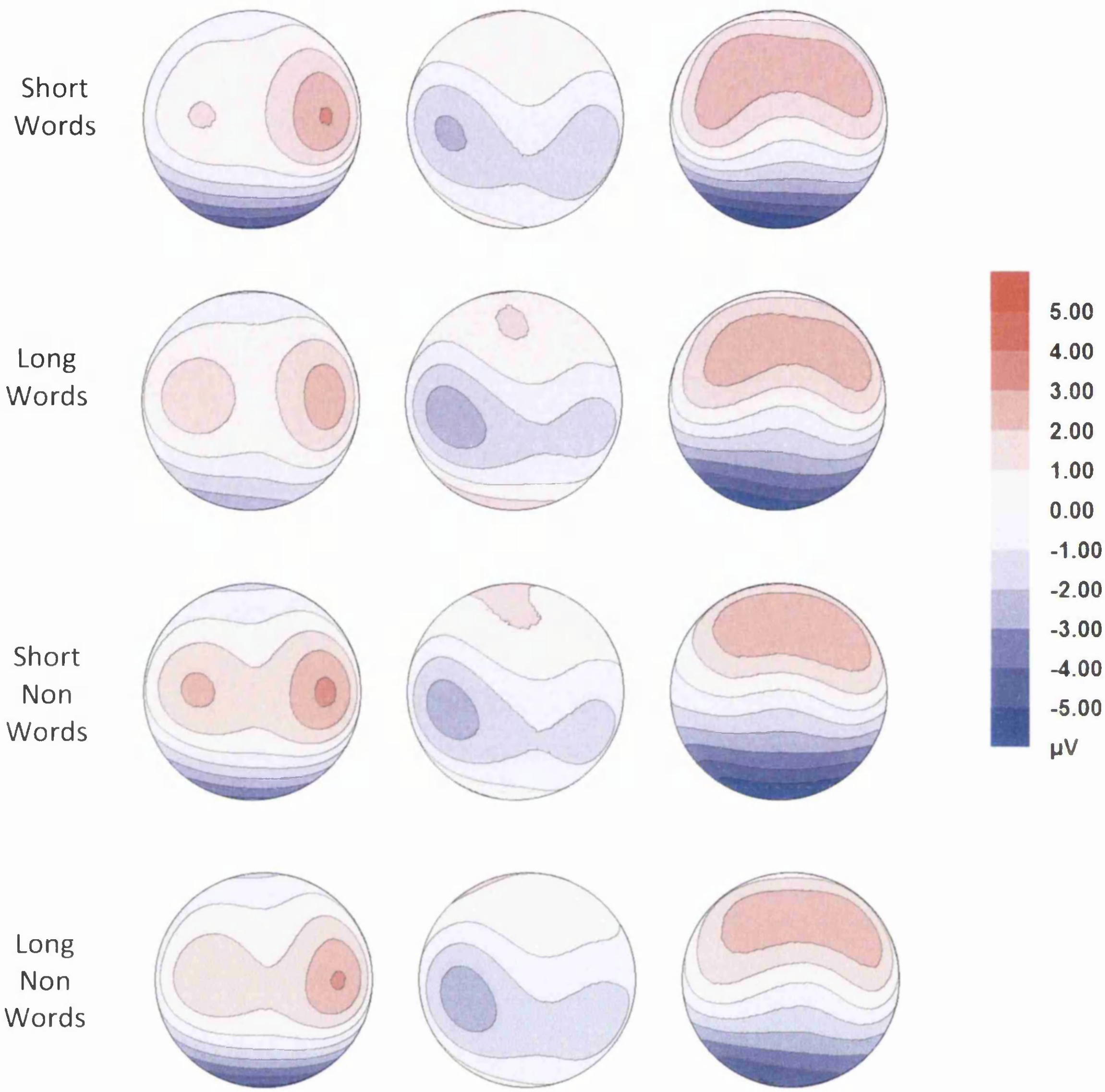
A clear effect of lexicality was present on the mean amplitude measure of the N170 component: $F(1,11)=5.10$, MSe = .632, $p < .05$, η^2_p = .32. Voltages generated by non-words (-1.24μv) were larger (i.e. more negative) than those evoked by words (-1.08μv). An interaction of lexicality and hemisphere indicated that the effect of lexicality differed between the hemispheres: $F(1,11)=6.28$, MSe = .811, $p < .05$, η^2_p = .36. In the LH, no effect of lexicality was present, with voltages to words and non-words being equally negative. In the RH, voltages to non-words were significantly more negative than those to words ($p < .05$). Furthermore, comparing across hemispheres, amplitudes evoked by words were significantly more negative in the LH than in the RH ($p = .05$). By contrast, amplitudes to non-words did not differ across hemisphere.

The interaction of lexicality and hemisphere was also reflected in the peak latency measures on the N170: $F(1,11)=11.80$, MSe = 1330.73, $p < .01$, $\eta^2_p = .52$. In the LH, words achieved their peak latency significantly earlier than non-words (178ms vs. 191ms; $p < .05$). In the RH, words and non-word peaked at equivalent latencies.

In terms of mean amplitude, there was no main effect of either hemisphere [$F(1,11)=2.55$, MSe = 16.37, $p = .14$, $\eta^2_p = .19$] or length [$F(1,11)=.43$, MSe = .33, $p = .43$, $\eta^2_p = .06$] and no interaction of the two factors [$F(1,11)=1.34$, MSe = .65, $p = .27$, $\eta^2_p = .11$]. There was similarly no interaction of length and lexicality [$F(1,11)=.68$, MSe = .11, $p = ..43$, $\eta^2_p = .06$] or three-way interaction of hemisphere, length and lexicality [$F(1,11)=.67$, MSe = .06, $p = ..43$, $\eta^2_p = .06$].

4.1.2.2.4 ~300ms Mean Amplitude and Peak Latency

Word length exerted a robust effect at 300ms: $F(1,11)=28.85$, MSe = 13.00, $p < .001$, $\eta^2_p = .72$, with short words (1.74μv) evoking significantly higher voltages than long words (1.01μv). Lexicality also influenced mean amplitudes at 300ms [$F(1,11)=15.29$, MSe = 5.27, $p < .005$, $\eta^2_p = .58$], with words (1.14μv) generating larger responses than non-words (1.61μv).



An interaction of lexicality and hemisphere was evident at 300ms: F (1,11)=7.24, MSe = 1.13, $p < .05$, $\eta^2_p = .40$. At 300ms, non-words (2.09μv) evoked larger voltages than words (1.4μv) in the LH. In the RH, words and non-words evoked statistically equivalent voltages.

At 300ms, hemisphere also interacted with length: F(1,11)=6.34, MSe = 1.85, $p < .05$, $\eta^2_p = .37$. Significant effects of length were present in both hemispheres; however, the difference between short and long items in the LH (1.01μv) was larger than in the RH (.46μv).

Finally, an effect of length was present on peak latencies at 300ms : $F(1,11)=8.57$, MSe = 3182.45, $p < .05$, $\eta^2_p = .44$. Long words (283ms) reached their peak amplitude significantly earlier than short words (294ms).

In terms of mean amplitude, there was no main effect of hemisphere [$F(1,11)=4.32$, MSe = 12.85, $p = .06$, $\eta^2_p = .28$], no two-way interaction of length and lexicality [$F(1,11)=0.58$, MSe = .01, $p = .81$, $\eta^2_p = .005$] and no three-way interaction of hemisphere, length and lexicality [$F(1,11)=0.25$, MSe = .001, $p = .88$, $\eta^2_p = .002$].

4.2 Discussion

The present experiment sought to establish the effect of varying the length of centrally-presented words and non-words on the ERP brain response in the left and right cerebral hemispheres. The results of the behavioural task are clear: participants identified short words and non-words faster than long words and non-words. Response accuracy did not differ in respect of length for either words or non-words.

This finding of a length effect for centrally-presented words is in keeping with previous work that has identified inhibitory effects of increasing word length in word recognition tasks (Balota & Chumbley, 1984; Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; O'Regan & Jacobs, 1992; Ziegler, Perry, Jacobs, & Braun, 2001). In the present study, the size of the length effect between 4- and 8-letter strings was 71ms for words and 52ms for non-words. These figures are in line with O'Regan and Jacobs (1992), who found that increasing word length increased response latencies by approximately 15-19ms per letter. This suggests that length exerted effects of similar size on both words and non-words. These findings conflict with the results of Weekes (1997), who found that increasing word length affected the processing of non-words but not words. Weekes explained this finding by arguing that words and non-words are processed by different mechanisms, with non-words processed by a sequential, non-lexical strategy which is sensitive to increasing word length.

There were some important differences between the present study and that of Weekes (1997). Most notably, stimuli in Weekes' study were 3, 4, 5 or 6 letters in length, whereas in the present study, stimuli of 4- and 8- characters in length were chosen such that the difference between word lengths was maximised without using excessively long or short words. This, along with better-matched sets in terms of word frequency might explain why a robust effect of length was present in the response times of the present experiment but not in Weekes' (1997) study.

Thus, the behavioural findings of the present study found a robust effect of word length when words and non-words were centrally-presented, with the magnitude of the length effect being similar for words and non-words. Given that the size of the length effect for both words and non-words is in line with the per-letter increase in response latency reported by O'Regan and Jacobs (1992), the current data support the idea that words and non-words might be processed in a similar way: that is, in a sequential, non-lexical manner.

The main findings from the ERP analysis will now be discussed. In general, the results can be summarised as follows: 1) the earliest effects of length were apparent at 100ms, with long items generating the largest responses. The effect of length differed across hemispheres, with the LH demonstrating an effect of length on ERP responses for non-words but not words, and the opposite pattern in the RH. 2) N170 responses to words were larger over the LH than the RH. For non-words, N170 voltages were similar in each hemisphere. No effects of length were evident on the N170. 3) At 300ms, short words generated larger responses than long words, and non-words larger responses than words. An effect of length was evident in both hemispheres, with the difference between short and long items being larger in the LH.

At 100ms, ERP responses showed a hemispheric asymmetry, with mean amplitudes over the RH being larger than those in the LH. This is in agreement with several studies such as Hauk and Pulvermüller (2004), who found a marginally significant effect of hemisphere between 80-125, with larger effects over the RH. Similarly, in a regression analysis, Hauk et al. (2006) also found that activity at 100ms was right-lateralised. This suggests that at around 100ms the RH generates larger responses to centrally-presented words (both short and long) than the LH.

Amplitudes at 100ms were also affected by string length, with long items generating larger responses than short items. This is consistent with the findings of Hauk et al. (2006; 2009), who also found stronger responses to long words than short words starting from 90-100ms, with activity located in parieto-temporal-occipital areas. This was the case in the present study, where electrode clusters over parieto-occipital areas were employed. Taken together, these converging results suggest that the length effect evident at 100ms is generated in posterior areas.

Hauk and Pulvermüller (2004) also reported larger responses to long words than short words between 80-125ms. However, they noted that on the basis of their data, it was difficult to determine if this early length effect was due to the length of the word itself or due to the physical properties of the stimulus (i.e. long words may emit more luminance than short words). The present study is able to contribute to and extend the findings of Hauk and Pulvermüller (2004), as the interaction of lexicality, length and hemisphere at 100ms demonstrates that the effect of length differs by hemisphere and target lexicality. In the LH, mean amplitudes to non-words were affected by length, whereas amplitudes to words were statistically similar. In the RH, the reverse was true, with a marginally significant length effect for words but not non-words. If the length effect is caused by stimulus luminosity, an independent effect of length but no interaction with lexicality would be expected. The interaction found between length, lexicality and hemisphere in the current study suggests that this early length effect is not a simple function of the luminosity of the stimuli. Thus, luminosity was not a confounding variable in the present study. Furthermore, the current data support the view that activity in each hemisphere is differentially sensitive to lexicality and increasing word length at around 100ms. This supports the findings of Sereno and Rayner (2003), who found the earliest effects of lexicality at 112ms.

At 170ms, amplitudes for words demonstrated a hemispheric asymmetry, such that voltages recorded over the LH were more negative than those over the RH. This replicates Hauk and Pulvermüller's (2004) findings of a leftward asymmetry for words at around 170ms. Furthermore, in the present study, amplitudes evoked by non-words did not differ between hemispheres. This is in line with previous work that examined the N170 response in English-speaking participants that also identified a leftward N170 asymmetry for words but not for non-words (Maurer, Brandeis, & McCandliss, 2005).

Between 210-260ms, Hauk and Pulvermüller (2004) found an interaction of length and hemisphere, with the difference between short and long words being larger over the LH electrode cluster than the RH. In contrast, the current study found no length-related effects at 170ms, either in mean amplitude or peak latency measures. This seemingly conflicts with several studies that have reported length-related effects in time-ranges spanning 150-200ms, the time at which the N170 peaks. For example, Hauk and Pulvermüller (2004) report larger responses to short than long words for two time windows between 150-190ms and 210-260ms. Consistent with this is Van Petten and Kutas (1990), who also found larger responses to short words between 150-225ms.

The lack of length effect on the N170 in the present study may be explained by the different windows of analysis employed in various studies. For example, in the present study, a 100ms window was used to measure amplitude and peak latency of the N170. By contrast, Van Petten and Kutas (1990) used a 75ms window and Hauk and Pulvermüller (2004) used two time windows to span the N170 period, 150-190ms and 210-260ms. Thus, it may be the case that the time-window used in the present study may have been too large for any length effect to be detected.

However, there is another plausible explanation. As previously discussed, several studies have identified a 'cross-over' effect of length, such that responses to long words are stronger at earlier latencies, whilst short words generate greater activity at later time-points (e.g. Hauk & Pulvermüller, 2004; Hauk et al. 2006; Hauk et al., 2008). This was supported by the regression-based analysis of New et al. (2006), who suggested that the effect of length may not be linear. Given the evidence from ERP studies, the U-shaped function that New et al. (2006) propose may be present in the electrophysiological response by a time-dependent effect of length. This would account for why long words generate larger responses earlier on, with short words generating larger signals later in the processing stream. If this is the case, it may be that there is a point in time at which the cross-over effect occurs. In the present study, this cross-over point could have occurred at around 170ms. This suggestion is based on the fact that responses before the N170 time-window were larger for long words and responses after the N170 time-window were larger for short words. Therefore, the lack of length effect at 170ms could reflect a crossing-over or shifting effect of word length.

Lexicality and length exerted independent main effects at 300ms, with responses to non-words being larger than those to words and responses to short words being larger than those to long words. This is in general agreement with the behavioural data, which showed a significant effect of length for words.

Length and hemisphere interacted at 300ms. Amplitudes generated by short words were larger than those to long words in both hemispheres, although this difference was larger in the LH than the RH. This appears to be similar to the length by lexicality interaction observed by Hauk and Pulvermüller (2004) between 210-260ms. Whilst it is by no means certain the interactions observed in both studies are the same, as the time-windows used by Hauk and Pulvermüller (2004) and the present study overlap by 20ms, it is possible that the effect described by Hauk and Pulvermüller (2004) is captured in the ERP by the present study at around 300ms.

The aim of the present study was to investigate the effect of word length in each of the cerebral hemispheres using centrally-presented words and non-words. Behaviourally, a robust effect of length was found for both words and non-words in term of response times, with the magnitude of this length effect being of a similar size for both words and non-words. Whilst these behavioural results indicated that words and non-words may be processed in similar ways, the ERP analysis provided evidence for differential processing of words and non-words in each of the hemispheres. For the LH, a lexicality effect was present on mean amplitudes as early as 100ms post-stimulus onset, with amplitudes varying by length for non-words but not for words. This lexicality effect was also present in the LH at 170ms, at which time words reached peak activity significantly earlier than non-words. The effect was also present in the LH at 300ms, when non-words elicited larger amplitude responses than words. In the RH, the only difference between words and non-words was at 170ms, when amplitudes to non-words were more negative than those to words, although words and non-words reached peak activity at similar latencies. Thus, the LH demonstrated a consistent difference between words and non-words across all time windows, whereas the RH seemed less sensitive to the difference between words and non-words. This supports the view that there are two processing routes or 'modes' (i.e lexical and non-lexical), both of which are available to the LH (such that it can discern words from non-words and process each accordingly), with the RH only having access to the non-lexical mode, with which it much process both words and non-words alike. Thus, whilst the results of the present experiment suggest a robust behavioural effect of length that affects the processing of words and non-words alike, the results of the ERP analysis shed light on the way in which each of the hemispheres responds to words and non-words.

In general, the results of the electrophysiological analysis add to and extend the findings of previous research in this area by showing that a time-dependent effect of word length is present in the ERP waveforms, with long words generating larger responses earlier on and shorter words becoming most active later in the processing stream. Furthermore, this study has contributed to understanding in this area by demonstrating that the effect of length observed at 100ms is not attributable to the differing luminosity of short and long words. Instead, each hemisphere is differentially sensitive to target lexicality and string length at 100ms.

A LH asymmetry for words and not non-words at 170ms confirmed the sensitivity of the LH N170 response to familiar letter-strings. The lack of length effects on the N170 component could represent the point at which the activity generated by short and long words 'crosses-over', with responses to short words becoming larger after this point. Finally, at 300ms, an effect of length was present in both hemispheres. This was reflected in the behavioural data, which showed an effect of word length for words and non-words alike.

The results of the present experiment strongly suggest that each of the hemispheres is differentially sensitive to the length of centrally-presented words and that this effect may be both dynamic and time-dependent. However, presenting words centrally means that a copy of the word is directed to each of the hemispheres. To fully explore the effect of word length on each of the hemispheres independently, an experimental paradigm must be used that can effectively deliver stimuli directly to a chosen hemisphere. The following chapter reports the results of experimental work that uses a lateralised lexical task in combination with ERP measures to continue the investigation of the effect of word length on each of the hemispheres.

Chapter 5: The neural basis of the length by visual field interaction

Results from Experiment 1 (Chapter 4) showed electrophysiological evidence supporting the idea that word length has a differential impact on each of the cerebral hemispheres. However, it was also noted that judging the performance of the hemispheres based on data from central presentation alone may provide only a limited picture of how each of the hemispheres respond to increasing word length. To fully ascertain the effect of word length on each of the hemispheres, a mode of stimulus presentation must be employed such that each hemisphere can be stimulated independently by words of different lengths. As reviewed in Chapter 2, a number of behavioural studies have employed lateral stimuli presentation methods, such as the divided visual field technique (DVF; Bourne, 2006) to ensure the independent stimulation of the right (RH) and/or left hemisphere (LH). However, as reviewed in Chapter 3, the successful use of such tasks is dependent upon being able to directly stimulate the hemisphere of choice, with some questioning the ability of participants to do this on the basis of instructions alone (Jordan, Patching, & Milner, 2003). Clearly, a measure of how successful a lateral stimulus presentation is in stimulating the intended hemisphere would be useful to establish the validity of the DVF technique.

Event-related potentials offer just such a measure. Early visual potentials, such as the P1 and N1/N170 components, are known to be affected by the location of the stimuli in the visual field (Luck, 2005). In particular, hemispheric activity to words presented in the contralateral visual field typically differs from the activity generated by words presented in the ipsilateral visual field in terms of the ERPs amplitude and latency. For example, in a DVF word repetition study, Doyle and Rugg (1998) found that both P1 and N1 components peaked earlier for contralateral than for ipsilaterally-presented word stimuli. Similarly, several authors have reported that N1 amplitudes are larger for contralaterally-presented items than ipsilaterally-presented items (Coulson, Federmeier, Van Petten, & Kutas, 2005; Doyle & Rugg, 1998; Hillyard & Anllo-Vento, 1998). Differences in the timing of P1/N1 latencies may be attributable to inter-hemispheric transmission (IHTT), which is measured in ERP studies as the difference in latency between a directly-presented stimulus (i.e. contralateral to the target hemisphere) and an indirectly-presented stimulus (i.e. ipsilateral to the target hemisphere). In the first instance, a laterally presented stimulus projects directly to the primary visual cortex of the contralateral hemisphere. However, the same stimulus may also stimulate the ipsilateral hemisphere indirectly via the corpus callosum. Therefore, the difference in peak latencies between contralaterally- and ipsilaterally-presented stimuli is likely a product of callosal transfer time and is thought to be in the order of magnitude of about 10-15ms (Saron & Davidson, 1989).

Therefore, ERP studies that use a DVF task offer the possibility of determining how successful a lateralised presentation of stimuli is in stimulating the intended hemisphere. This can be established by the presence of an interaction between hemisphere and visual field since an interaction would indicate that stimuli presented contralaterally generated a different response to stimuli presented ipsilaterally. Surprisingly, however, few studies to date have made use of DVF techniques in combination with ERPs to examine the performance of each of the hemispheres during visual word recognition. Fewer still have manipulated word length.

In a study combining behavioural, ERP and fMRI measures, Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, Hénaff, and Michel (2000) identified early and late N1 neural activity evoked by presenting words and unpronounceable consonant strings to the left and right visual fields of five participants in a silent word-reading experiment. Word length was not orthogonally manipulated; instead, all words were between four and six letters in length and word length was controlled by matching across stimuli sets. Cohen et al. (2000) found that an early component of the N1 wave form, which emerged 150-160ms post-stimulus, was present strictly contralateral to the stimulated hemifield and showed no effect of target lexicality, when comparing words and consonant strings. They concluded that, at 150ms, brain responses are strongly affected by where the word is presented in the visual field but are relatively insensitive to lexicality (i.e., whether the target was a real word or a non-word). At 180-200ms post-stimulus onset, the impact of stimulus location appeared to have waned, as ERP responses to LVF- and RVF-presented words were now highly similar over LH temporal electrodes. On the basis of these data, Cohen et al. (2000) proposed that at 150ms, words are processed by two separate systems, one in each hemisphere, each dedicated to the contralateral visual field. However, by 180ms, the locus of processing has shifted to LH occipito-temporal regions for both LVF and RVF-presented words alike. This is in line with the view that the LH is the dominant language processor in left handed-participants.

The fMRI findings of Cohen et al. (2000) suggest that the late N1 activity at 180ms could be the electrical signature of the VWFA, which is thought to be involved in location-invariant word recognition. This is supported by the fact that Cohen et al. (2000) found that the fMRI BOLD response generated by the VWFA was equal in magnitude to both LVF and RVF-presented words. Taken together, these ERP and fMRI data suggest that from 180ms onwards, the physical location of a word ceases to impact upon its subsequent processing and all words are processed in a similar manner, irrespective of their original position in the visual field. On the basis of this finding, Cohen et al. (2000) suggested that the activity recorded over the LH at 180ms may be the neural concomitant of the right visual field advantage typically observed in lexical tasks. The ERP findings of Cohen et al. (2000) were recently replicated by Cai, Lavidor, Brysbaert, Paulignan, and Nazir (2008) with a group of eight individuals with left hemisphere dominance. Cai et al., (2008) also observed the late N1 (188-233ms) as the potential electrical signature of the VWFA in right hemisphere dominance individuals, just as it happened for their left hemisphere dominant counterparts. However, responses were this time stronger over the right hemisphere indicating that the word recognition system (e.g., VWFA) lateralizes to the regions where other language structures are based.

These findings have recently been challenged. Barca, Cornelissen, Simpson, Urooj, Woods, and Ellis (2010) have argued that the well-known behavioural advantage for orthographic stimuli presented in the RVF should be reflected in the brain's response to printed words. In particular, they suggest that the responses of the

VWFA should demonstrate stronger and/or faster responses to RVF-words than LVF-words, reflecting the processing advantage enjoyed by words presented to the RVF and so often observed in behavioural studies. Barca et al. (2010) suggest that the fact that Cohen et al. (2000) and Cai et al. (2008) found no hemifield-dependent effects on VWFA activity after 200ms is problematic as it is unclear from their respective data how the behavioural RVF advantage might be represented in the brain's neural response. Barca et al. (2010) used MEG beamforming and virtual electrode approaches to measure activity in each of the hemispheres evoked by words presented to the left and right visual fields. Stimuli were all 5-letter words and non-words, with each item being presented to the LVF and the RVF equally often across six trial blocks. Scrambled words were used as non-words but still kept the visual properties of words, to act as a control condition. Twenty participants (six of whom were subsequently rejected due to excessive artefacts) were asked to perform a silent word reading task whilst in a MEG scanner.

Analysis of virtual electrodes located at the inferior occipitotemporal cortex, an area that includes the VWFA found stronger responses to RVF words than LVF words at 80ms which persisted until 375ms. This result conflicts with Cohen et al.'s (2000) findings of VWFA responses being of equal magnitude to LVF and RVF words. Furthermore, beamforming analysis showed significant increases in power to contralaterally-presented words as opposed to ipsilaterally-presented words between 0-200ms. This is consistent with the pattern of P1/N1 ERP activity reviewed above, which is likely to be indicative of the relative success of the experimental paradigm in stimulating the intended hemisphere (Doyle & Rugg, 1998).

Thus, electrophysiological findings have indicated that P1 and N1 components should be faster and/or larger for contralateral than for ipsilateral presentation (Doyle & Rugg, 1998). However, Cohen et al., (2000) and Cai et al., (2008) have shown that, in the LH, a late portion of the N1 - the N170 – which is thought to be the electrical signature of the VWFA is unaffected by the position of a target in the visual field. Using MEG, Barca et al., (2010) have found hemifield-dependent activity in the VWFA that persists until 375ms. As such, the little available neuroimaging evidence concerning the right visual field advantage and the conflicting results reported by these few existing studies mean that there remains much uncertainty concerning how the right visual field advantage is reflected in the brain's neural response.

Of the studies reported above, none manipulated the length of words. As the presence (or absence) of a length effect in each of the visual fields has been viewed as a marker of the type of processing occurring in a given hemisphere in response to written words (see Chapter 1 for a review of these studies), neuroimaging studies in which the length of words was manipulated will now be briefly reviewed. The number of studies exploring the length effect in response times and accuracy is large; however, there is surprisingly just one study to date that has investigated brain-related activity in response to increasing word length in the left and right visual fields.

Cohen, Dehaene, Vinckier, Jobert, and Montavont (2008) investigated the effect of stimulus degradation on word recognition using fMRI. Although primarily focused on centrally-presented stimuli, Cohen et al. (2008) included a condition where targets were either presented centrally or visually degraded by displacing them 75% or 100% left or right of fixation. Twelve participants performed a semantic decision task on a total of 210 words of 4, 5 and 6 letters in length.

Behaviourally, Cohen et al. (2008) found that RTs only increased as a function of word length when target items were either 75% or 100% displaced into the LVF. This is in line with the general behavioural finding that increasing word length has a larger effect on the LVF than the RVF. Correspondingly, fMRI data showed that whilst the left occipitotemporal cortex was strongly affected by some modes of stimulus degradation (such as rotation or non-canonical letter spacing), it was insensitive to word displacement – that is, activations were statistically similar, irrespective of where the word was presented in the visual field. The lateral displacement of words was found to be particularly associated with activity in mesial posterior parietal regions (including right precuneus and left retrosplenial cortex). On this basis, Cohen et al. (2008) argue that stimuli degraded above a certain threshold - in this case, 75% or 100% displacement into the LVF – are associated with a shift in processing strategy away from fast, automatic ventral processes (such as that engage VWFA processing) towards posterior parietal regions, which are thought to be active when stimuli are particularly degraded or unfamiliar. Processing of words by these regions is assumed to be slower and more sequential in nature, resulting in a monotonically increasing effect of word length.

Finally, in an attempt to explore the cerebral basis of the effect of word length, Cohen et al. (2008) contrasted activation of 4- and 6-letter words. They predicted that word length would evoke activity in the same posterior parietal areas as were active when stimuli were degraded through rotation and letter spacing. The fact that Cohen et al. (2008) found no such length-related activity may be due to the fact that they were contrasting 4- letter words against 6-letter words. This represents a relatively small difference in string length. Furthermore, although words were displaced to the left and right, in all cases, at least part of the stimulus was displayed within the foveal region, even at 100% displacement. Typically, DVF studies present stimuli in the parafoveal visual fields, starting from ~2˚ to the left or right or fixation (Bourne, 2006). In Cohen et al.'s (2008) study, 75% displaced stimuli straddled fixation by one character and 100% were immediately to the left or to the right of fixation. As such, it is unclear how successful the displacement of words was in directly stimulating each hemisphere. In conclusion, it is possible that the experimental design of Cohen et al. (2008) may not have been sensitive enough to detect reliable length effects, presuming that they were, indeed, present.

The aim of the present study is to examine the effect of word length on the electrophysiological response of each of the cerebral hemispheres during a divided visual field task. For the behavioural task, it is predicted that increasing word length will have a larger impact on the RH than the LH for words and an equal impact on each hemisphere for non-words. On the basis of the material reviewed above, two predictions about the ERP task can be made. Firstly, it is predicted that P1 and N1 responses should be stronger for contralateral vs. ipsilateral stimuli. Thus, the presence of an interaction of visual field and hemisphere on the P1 and N1 components will serve as an index of how effectively the DVF paradigm stimulates the intended hemisphere. Secondly, as both Cohen et al. (2000) and Barca et al. (2010) identified 150-250ms as being a key time-window in the recognition of laterally-presented words, it is predicted that the interaction of length and visual field for words, which is a common finding in the behavioural word recognition literature, will be reflected in mean amplitude and peak latency measures at ~200ms.

5.1 Experiment 2

5.1.1 Method

5.1.1.1 Participants

Twenty-two monolingual native English-speaking students at Swansea University (6 male, 16 female), participated in the experiment. None of the participants had taken part in Experiment 1. All participants had normal or corrected to normal vision and were between the ages of 18-46 (mean age: 22). All were rated as strongly right handed by the Edinburgh Handedness Inventory (>80%; Oldfield, 1971). Participants received £15 or course credits in return for their participation.

5.1.1.2 Materials

The materials used in this experiment comprised the same 200 words and 200 orthographically legal non-words used in Experiment 1 (Chapter 4). Half of the stimuli were 4 letters in length and half 8 letters in length. Item lexicality (word/non-word), letter length (short/ long) and visual field presentation (RVF/LVF) were orthogonally manipulated, leading to eight experimental conditions (i.e., (1) four-letter words presented in the RVF; (2) four-letter words presented in the LVF; (3) eight-letter words presented in the RVF; (4) eight-letter words presented in the LVF; (5) four-letter non-words presented in the RVF; (6) four-letter non-words presented in the LVF; (7) eight-letter non-words presented in the RVF and (8) eight-letter non-words presented in the LVF). Words and non-words were not repeated across conditions but presented once only. Therefore each condition consisted of 50 stimuli.

5.1.1.3 Apparatus and procedure

The experiment began with 40 practice trials (20 words and 20 non-words), different from those used as experimental stimuli but maintaining the same string lengths (4-letters and 8-letters items). Stimuli were laterally displaced such that the last letter of LVF and the first letter of RVF stimuli were 2° from fixation. The procedure was the same as that employed in Experiment 1, apart from the fact that were eight experimental conditions as words and non-words were presented in the left and right visual fields.

5.1.1.4 ERP Acquisition, Processing and pre-processing

Acquisition and pre-processing procedures were the same as in Experiment 1 (Chapter 4).

5.1.2 Results

5.1.2.1 Behavioural Results

Response times (RTs) of less than 150ms and more than 2.5 standard deviations from the mean were treated as outliers and removed from further analyses (2.7% of all trials). Thirteen percent of responses were participant errors and rejected from RTs analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 5.1.

Table 5.1. Mean reaction times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of visual field (LVF vs. RVF), word length (short 4-letter vs. long 8-letter) and target lexicality (word vs. non-word) in Experiment 2.

	WORDS					
	Left Visual Field			Right Visual Field		
	Short	Long	Difference	Short	Long	Difference
M	430	509	79	425	475	50
SD	146	163		171	174	
% Acc	91	85		92	88	

	NONWORDS					
	Left Visual Field			Right Visual Field		
	Short	Long	Difference	Short	Long	Difference
M	559	598	39	551	581	30
SD	186	239		193	216	
% Acc	85	77		82	77	

Only correct responses were analysed. A repeated-measures ANOVA was conducted on the RT data by subjects (F_1), with word length (short vs. long) and VHF (LVF vs. RVF) as within-subjects factors. A by-items analysis (F_2) was also conducted, with word length and VHF as between-subjects factors.

5.1.2.1.1 Responses to words

Short words were recognised faster than long words in both by-subjects and by-items analyses: $F_1(1,21) = 122.54$, MSe = 92229.94, $p < .001$, $\eta^2_p = .85$, $F_2(1,196) = 65.68$, MSe = 216368.588, $p < .001$, $\eta^2_p = .25$. Overall RTs to long words (492 ms) were significantly slower than those of short words (427 ms).

A main effect of visual field was also found, with RVF-presented words (450ms) being recognised faster than LVF-presented words (470ms): $F_1(1,21) = 15.01$, MSe = 8812.12, $p < 0.001$, $\eta^2_p = .42$; $F_2(1,196) = 5.48$, MSe = 18065.54, $p < 0.001$, $\eta^2_p = .30$.

The interaction of word length and visual field was significant by-subjects and approached significance by-items: $F_1(1,21) = 9.29$, MSe = 4457.14, $p < 0.01$, η^2_p = .31; $F_2(1,196) = 3.04$, MSe = 10003.65, $p = 0.08$, η^2_p = .02. The by-subjects interaction is depicted in Figure 5.1. The nature of the interaction was such that the impact of increasing word length was greater when the word was presented in the LVF than the RVF. By-subjects post-hoc pairwise comparisons indicated that there was no difference in RT to short words across visual fields (p> .1; LVF=435 ms and RVF=428 ms), whilst long words were recognised reliably faster (p<.05) when presented in the RVF (475 ms) than in the LVF (509 ms). The interaction of length and visual field approached significance in the by-items analysis (p = .08). Post-hoc comparisons indicated again that short words were responded to with equivalent latencies in both visual fields (LVF=433ms, RVF=428ms), whilst long words were identified reliably faster (p<.005) in the RVF (480ms) than in the LVF (513ms).

Two repeated-measures ANOVAs were conducted on the accuracy data: a by-subjects analysis (F_1), with word length (short vs. long) and VHF (LVF vs. RVF) as within-subjects factors and a by-items analysis (F_2), with word length and VHF as between-subjects factors.

A main effect of word length was found by-subjects and by-items, $F_1(1,21) = 12.364$, MSe = 410.23, $p < .05$, η^2_p = .37; $F_2(1,196) = 13.39$, MSe = 932.34.23, $p < .001$, η^2_p = .06. Across conditions, responses to short words were more accurate (91%) than responses to long words (87%). No other main effects or interactions were found.

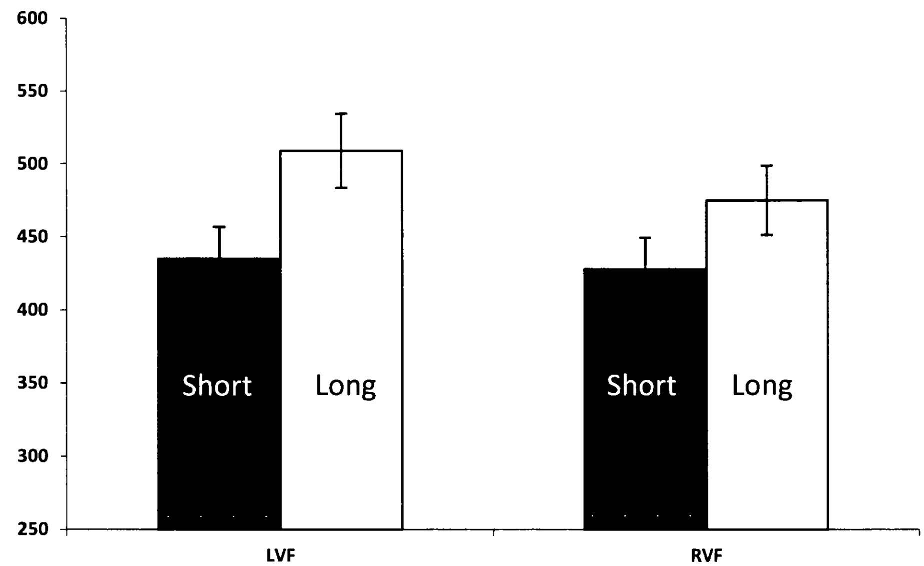


Figure 5.1: Graph of length by visual field interaction for words. Short words were recognised equally quickly in both visual fields. Increasing word length had a larger effect on the LVF than the RVF. *y*-axis is RT measured in milliseconds.

5.1.2.1.2 Responses to non-words

The same by-subjects and by-items analyses for RT and accuracy as were conducted on data for words were also applied to non-words.

For reaction times, a main effect of length was found by-subjects and by-items, $F_1(1,21) = 15.20$, MSe = 37006.65, $p < .01$, $\eta^2_p = .42$; $F_2(1,196) = 19.88$, MSe = 63216.13, $p < .001$, $\eta^2_p = .09$. Responses to short non-words (553 ms) were significantly faster than to long non-words (594 ms). No other main effects or interactions approached significance.

For accuracy, the main effect of length was significant by-subjects and by-items, $F_1(1,21) = 8.38$, MSe = 37006.65, $p < .01$, $\eta^2_p = .29$; $F_2(1,196) = 9.40$, MSe = 1827.38, $p < .01$, $\eta^2_p = .05$. Short non-words yielded more accurate responses (84%) than long non-words (77%). No main effect of visual field or interaction of word length and visual field was found.

5.1.2.2 Electrophysiological Results

Only trials with correct responses were included in ERP analyses. Grand average RMS curves (Figure 5.2), plotted for all conditions across time, indicated four main peaks in the ERP distribution, at 100ms, 180ms, 250 and 330ms post-stimulus onset. These peaks were considered for analysis since they occurred before the average response time of participants (460ms). For each peak, grand average topographies were examined and time-windows of interest were selected as follows: for the peak at 100ms, the maximal positive deflection between 70 and 130 ms (corresponding to the P1 component); for the peak at 180ms, the maximal negative deflection between 130 and 230ms (corresponding to the N170); for the peak at 250ms, the maximal positive deflection between 180ms and 280ms and for the peak at 330ms, the maximal negative deflection between 280 and 380ms over occipitotemporal sites. As in Experiment 1, analyses were focused on two groups of electrodes, formed from the average of PO3, PO7 and P7 over the left hemisphere and PO4, PO8 and P8 over the right hemisphere.

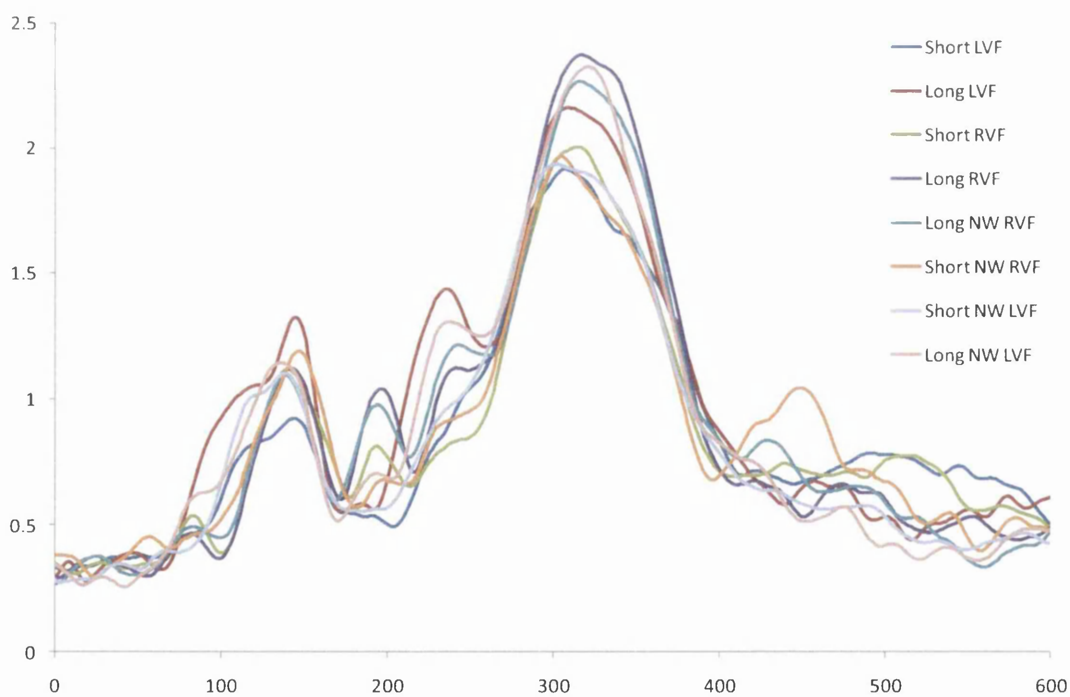


Figure 5.2 Grand average RMS curves for all conditions plotted across all electrodes

5.1.3 Preliminary Analyses

An initial analysis was conducted to assess the success of the current paradigm in stimulating the intended hemisphere. Therefore, activity evoked by contralateral and ipsilateral presentations was examined for P1 and N1 components. Table 5.2 presents mean amplitudes and peak latencies for P1 and N1 components for contra- and ipsilateral presentation collapsed across word length. Previous lateralised ERP studies have found that both P1 and N1 components peak earlier for contralaterally-presented than for ipsilaterally-presented stimuli (e.g., Doyle & Rugg, 1998) and that N1 amplitudes are larger for contralaterally-presented items than ipsilaterally-presented items (Coulson, Federmeier, Van Petten, & Kutas, 2005; Doyle & Rugg, 1998; Hillyard & Anllo-Vento, 1998). Thus, in the present analyses, an interaction between visual field and hemisphere was expected to serve as an index of how successfully stimuli were directed to the contralateral hemisphere.

Table 5.2: Mean Amplitude and Peak Latencies for P1 and N1 components evoked by contra- and ipsilaterally-presented words

	Left Hemisphere		Right Hemisphere	
	LVF	RVF	LVF	RVF
Amplitude				
P1	.96	-0.04	1.16	1.16
N1	1.12	-0.44	0.47	0.98
Latency				
P1	131	111	115	141
N1	185	167	172	193

Four repeated measures ANOVAs were conducted separately on latency and amplitude for the P1 and N1 components, with visual field and hemisphere as within-subjects factors in each analysis.

For the P1 component, a visual field by hemisphere interaction showed that amplitudes to contralaterally-presented stimuli peaked earlier than those to ipsilaterally-presented items: $F(1,19) = 27.65$, MSe = 10488.56, $p < .001$, $\eta^2_p = .59$.

Mean amplitudes were larger over the RH, irrespective of visual field: $F(1,19) = 4.462$, MSe = 9.09, $p < .05$, $\eta^2_p = .20$.

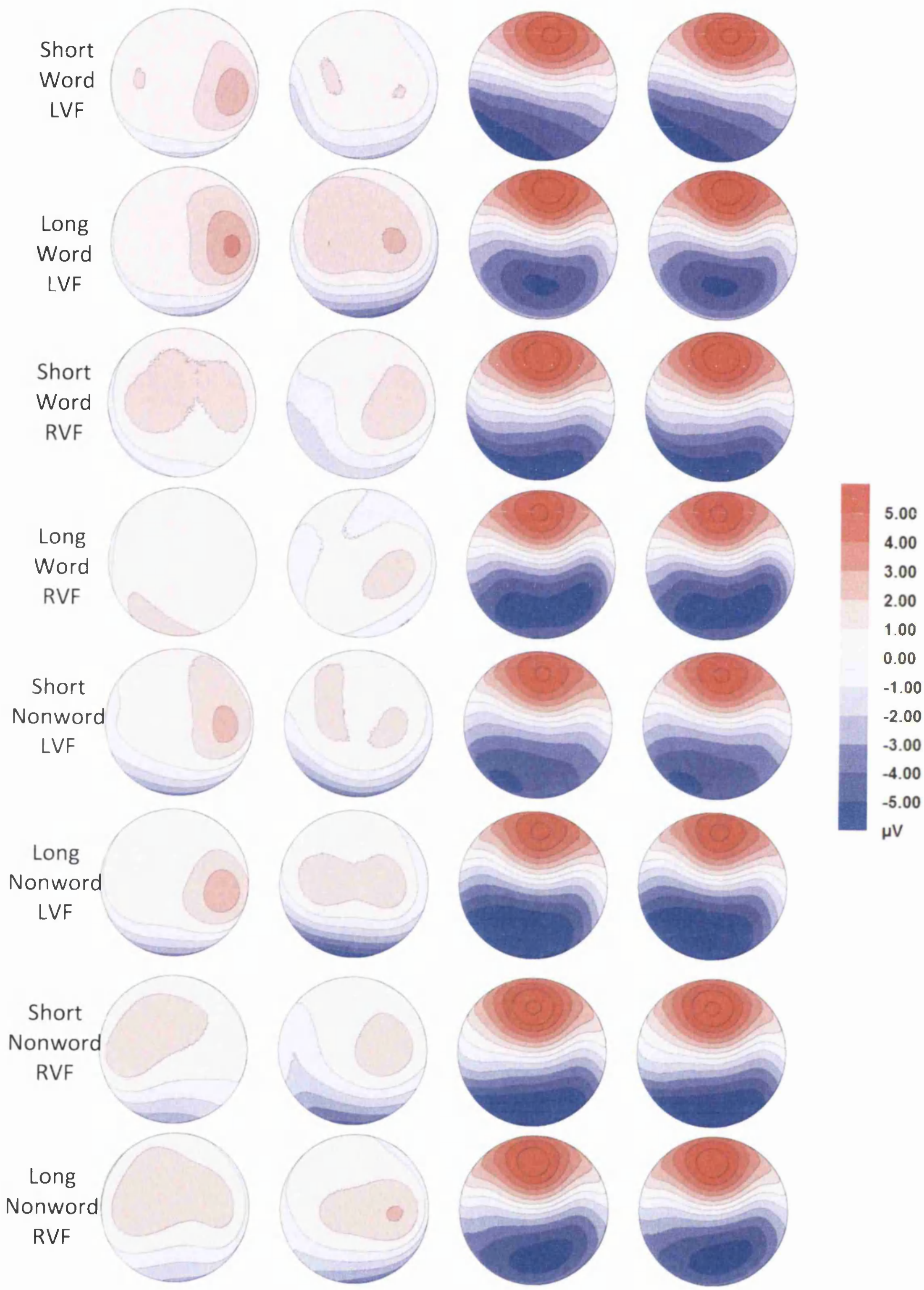
The interaction of visual field and hemisphere was also evident, in both mean amplitude and peak latency measures on the N1 component. In terms of latency, contralaterally-presented words achieved peak latency before ipsilaterally-presented items in both hemispheres: $F(1,19) = 15.95$, MSe = 7763.49, $p < .001$, $\eta^2_p = .46$. The interaction was also present for mean amplitudes: $F(1,19) = 11.47$, MSe = 21.56, $p < .005$, $\eta^2_p = .38$, with amplitudes to contralaterally-presented items being larger than those to ipsilaterally-presented items in both hemispheres.

These preliminary results indicate the paradigm was successful in stimulating the intended hemisphere. For simplicity, all subsequent analyses focus on contralaterally-presented items only. Words and non-words are analysed together. Mean amplitudes and peak latency were analysed using two repeated-measures ANOVAs, with lexicality (word vs. non-word), recording site (LH vs. RH) and string length (short vs. long) as within-subjects factors.

5.1.3.1 Event Related Potentials (ERPs)

5.1.3.1.1 Responses to words

Figure 5.3 presents topographic scalp maps of the rear of the head for all conditions plotted across all time windows. Figure 5.4 presents grand average ERP curves for all conditions plotted over the left and right hemispheres.


Short Word LVF
Long Word LVF
Short Word RVF
Long Word RVF
Short Nonword LVF
Long Nonword LVF
Short Nonword RVF
Long Nonword RVF
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
µV

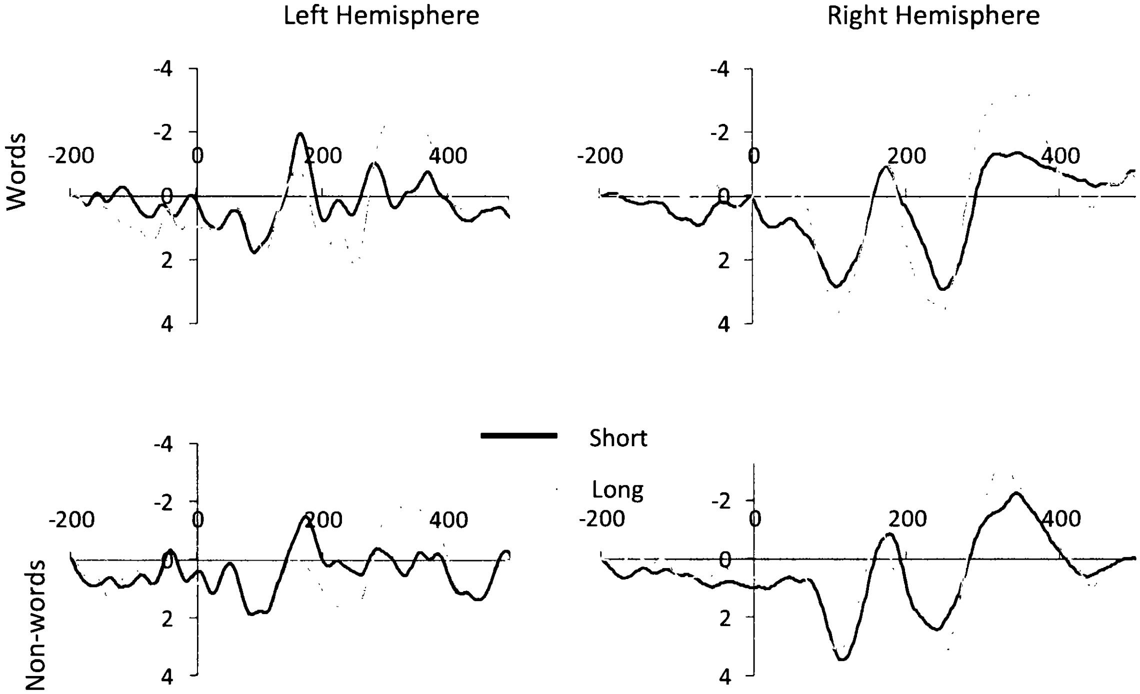


Figure 5.4 ERP curves for contralateral presentation, plotted over the left and right hemisphere.

5.1.3.1.2 P1 Mean Amplitude and Peak Latency

Mean amplitude of the P1 deflection was larger over the RH (1.10 μv) than the LH (0.1 μv) irrespective of where the item was presented in the visual field: $F(1,19) = 27.65$, MSe = 10488.56, $p < .001$, $\eta^2_p = .59$. There were no main effects of either lexicality [$F(1,19) = .38$, MSe = .117, $p < .55$, $\eta^2_p = .02$] or length [$F(1,19) = 3.09$, MSe = .1.64, $p < .10$, $\eta^2_p = .14$], no interaction of lexicality and hemisphere [$F(1,19) =$ .1.47, MSe = .1.42, $p < .24$, $\eta^2_p = .07$], lexicality and length [$F(1,19) = 1.25$, MSe = .77, $p < .28$, $\eta^2_p = .06$] or hemisphere and length [$F(1,19) = 1.25$, MSe = ..80, $p < .28$, $\eta^2_p = .06$] and no three-way interaction of lexicality, length and hemisphere [$F(1,19) =$ .4.18, MSe = 2.62, $p < .55$, $\eta^2_p = .18$].

No latency effects were present on the P1 component.

5.1.3.1.3 N1 Mean Amplitude and Peak Latency

A main effect of length was present on the N1 amplitudes: $F(1,19) = 9.90$, MSe = 9.08, $p < .005$, $\eta^2_p = .34$. Collapsed across item type and hemisphere, short items (-0.19μv) generated larger negativities than long items (.29μv). There was no main effect of either lexicality [$F(1,19) = .47$, MSe = .19, $p < .50$, $\eta^2_p = .02$] or hemisphere [$F(1,19) = 2.61$, MSe = 27.46, $p < .12$, $\eta^2_p = .12$], no interaction of lexicality and hemisphere [$F(1,19) = .21$, MSe = .27, $p < .65$, $\eta^2_p = .01$], lexicality and length [$F(1,19) = 1.10$, MSe = .56, $p < .31$, $\eta^2_p = .06$] or hemisphere and length [$F(1,19) = .001$, MSe = ..001, $p < .98$, $\eta^2_p = .000$].

The three-way interaction between lexicality, length and hemisphere indicated a differential effect of length on amplitudes evoked by words and non-words in each of the hemispheres: $F(1,19) = 4.30$, MSe = 2.87, $p = .05$, $\eta^2_p = .18$. This interaction is depicted in Figure 5.5. Post-hoc comparisons indicated that in the LH, an effect of word length was evident for non-words ($p = .02$), with short non-words eliciting larger negativities that long non-words. The difference between short and long words in the LH was not significant. In the RH, an effect of word length was evident for words, with short words generating more negative amplitudes than long words ($p = .01$). Amplitudes to short and long non-words presented to the RH did not differ ($p = ns$).

Peak latency analysis demonstrated a significant effect of length, with long words (166ms) reaching peak latency before short words (173ms): $F(1,19) = 8.74$, MSe = 1490.12, $p < .01$, $\eta^2_p = .32$.

An interaction of length and lexicality indicated that the effect of string length was driven by words: $F(1,19) = 9.85$, MSe = 1031.49, $p < .005$, $\eta^2_p = .41$. For words, long items reached peak latency 11ms earlier than short words ($p = .001$). For non-words, short items peaked just 1ms earlier than long non-words ($p = ns$).

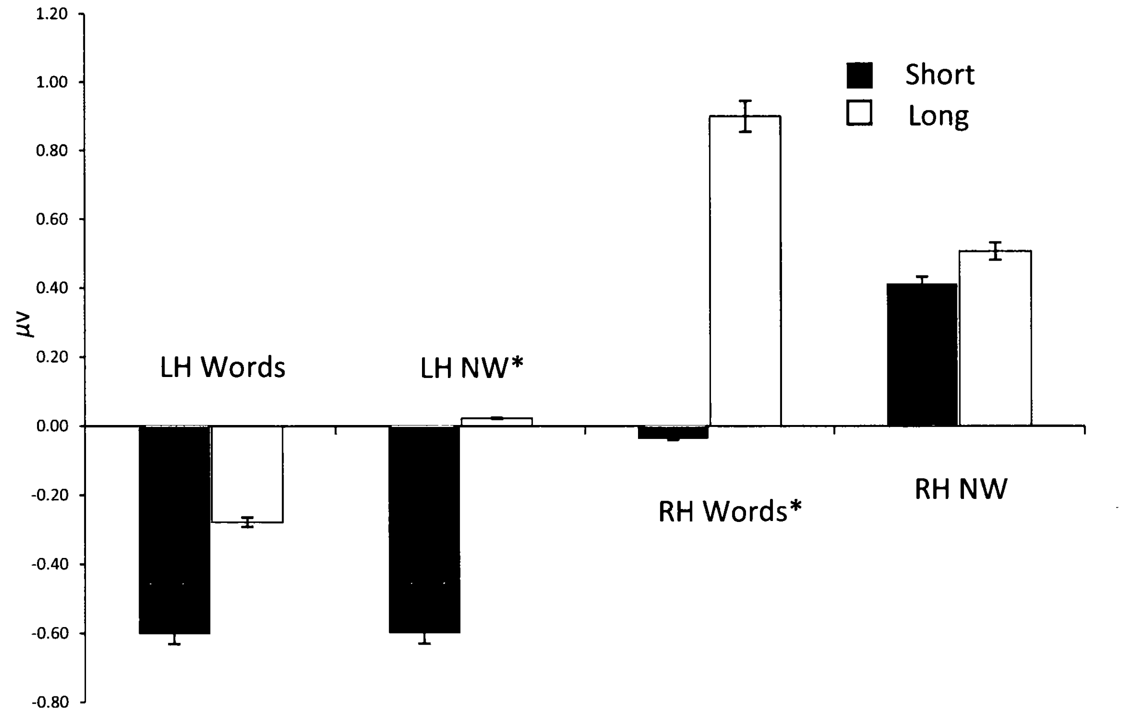


Figure 5.5 Mean amplitudes to contralaterally-presented words as a function of lexicality, string length and hemisphere, demonstrating a length effect for non-words but not words in the LH and a length effect for words but not non-words in the RH. Significant effects are indicated with an asterisk (*).

5.1.3.1.4 P2 Mean Amplitude and Peak Latency

Between 180 and 280ms, a significant main effect of length on mean amplitudes indicated that long items (1.6uv) generated larger positive-going deflections than short items (.8uv): $F(1,19) = 21.83$, MSe = 24.52, $p < .001$, $\eta^2_p = .53$. At the same time, a main effect of hemisphere was observed with amplitudes recorded over the RH (1.85uv) being more positive than those recorded over the LH (.53uv): $F(1,19) = 8.20$, MSe = 69.26, $p < .01$, $\eta^2_p = .30$. There was no main effect of lexicality [$F(1,19) = 0.7$, MSe = .04, $p < .80$, $\eta^2_p = .003$], no interaction of lexicality and hemisphere [$F(1,19) = 1.10$, MSe = .1.66, $p < .31$, $\eta^2_p = .06$], lexicality and length [$F(1,19) = .65$, MSe = .39, $p < .43$, $\eta^2_p = .001$] or hemisphere and length [$F(1,19) = .03$, MSe = .05, $p < .97$, $\eta^2_p = .001$] and no three-way interaction of length, lexicality and hemisphere [$F(1,19) = 2.04$, MSe = .1.43, $p < .17$, $\eta^2_p = .01$].

In the peak latency analysis, hemisphere and lexicality interacted $F(1,19) = 9.42$, MSe = 2335.76, $p < .01$, $\eta^2_p = .33$, such that in the LH, words (226ms) achieved peak latency before non-words (237ms). In the RH, words (245ms) and non-words (241ms) peaked at similar latencies. No other main effects or interactions pproached significance.

5.1.3.1.5 N2 Mean Amplitude and Peak Latency

A main effect of string length on mean amplitudes was identified [$F(1,19) = 17.88$, MSe = 44.13, $p < .001$, $\eta^2_p = .49$], with long items (-1.09uv) generating larger amplitudes than short items (-.04uv). There were no main effects of lexicality [$F(1,19) = .95$, MSe = 1.32, $p < .34$, $\eta^2_p = .05$] or hemisphere [$F(1,19) = .34$, MSe = 4.00, $p < .57$, $\eta^2_p = .02$], no interactions of lexicality and hemisphere [$F(1,19) = 4.07$, MSe = 7.36, $p < .06$, $\eta^2_p = .17$], lexicality and length [$F(1,19) = .97$, MSe = 1.24, $p < .34$, $\eta^2_p = .05$] or length and hemisphere [$F(1,19) = .13$, MSe = .13, $p <$ ..72, $\eta^2_p = .007$] and no three-way interaction between length, lexicality and hemisphere [$F(1,19) = .005$, MSe = .004, $p < .94$, $\eta^2_p = .00$].

No latency effects were found.

5.2 Discussion

The aim of the present study was to examine the effect of word length on the electrophysiological response of each of the cerebral hemispheres during a divided visual field task. Using a lateralised lexical decision task, participants identified words and non-words of varying lengths that were presented directly to their left and right hemispheres whilst EEG recordings were made. Standard behavioural measures of RT and accuracy were obtained, in addition to ERP measures of mean amplitude and peak latency.

As expected, behavioural data demonstrated an interaction of length and visual field for word targets, such that increasing word length had a larger impact on the RH than the LH. For non-words, an effect of length was apparent in both hemispheres. Since these data a) are entirely in line with previous behavioural studies that have manipulated word length in the visual fields (e.g Bub & Lewine, 1988; Ellis, Young, & Anderson, 1998) and b) served only as a reliable behavioural task known to elicit direct stimulation of the hemispheres from which ERP data of interest could be recorded, they will not be discussed further.

Preliminary analysis of the pattern of activity at P1 and N1 components indicated that the present paradigm was successful in stimulating the intended hemisphere. Analyses of the P1 component showed that, in both hemispheres, ipsilaterally-presented stimuli were delayed relative to contralaterally-presented stimuli, with larger amplitudes over the RH irrespective of where stimuli were presented. This pattern of responses is in good agreement with P1 activity measured by Doyle and Rugg (1998). In the present study, activity evoked in the left hemisphere by ipsilaterally-presented words peaked 20ms later than that for contralaterally-presented words; in the RH, the difference between contralateral and ipsilateral latencies was 26ms. As such, the transfer of information during the early stages of visual word recognition may be more efficient from RH to LH than from LH to RH. This is consistent with Barca et al. (2010), who also identified asymmetrical transfer of information between 100-350ms using MEG, with more efficient transfer RH-LH than LH-RH. Taken together, these results may suggest that the visual word recognition system is structured such that information about words, no matter where they are presented in the visual field, is efficiently transferred to the LH, the language-dominant processor.

If the difference between contralateral and ipsilateral latencies on the P1 component is representative of IHTT, then the callosal relay times reported in the present study are slightly slower than the 10-15ms effect suggested by Saron and Davidson (1989). This may be explained by the type of stimuli employed in the two studies. Saron and Davidson (1989) used a single, high-contrast checkerboard pattern as a stimulus. By contrast, the present study used 4- and 8- letter words. It is possible, therefore, that IHTT is slightly faster for simple, high-contrast stimuli that are frequently repeated than for words and non-words, which are more visually complex, multi-component stimuli.

The key finding arising from the present study was that an interaction of word length and hemisphere was apparent in the ERP analysis at 180ms (N1 component). At 180ms, LH amplitudes to contralaterally-presented words did not vary as a function of length whereas RH amplitudes to short words were significantly more negative than those to long words. This suggests that at 180ms, parietooccipital areas in the LH are relatively less sensitive to increasing word length for contralaterally-presented word targets than homologous RH areas. Furthermore, left hemisphere amplitudes to non-words were modulated by word length, suggesting that parietoccipital areas of the LH are specifically tuned to word but not non-word stimuli. This is in line with available behavioural evidence which suggests that the LH uses a fast, whole-word based mode of recognition for legal words and a more effortful, length-dependent mode for non-words. This was also supported by peak latency measures on the P2 component, which showed that, in the LH, words reached peak activity significantly earlier than non-words. In the RH, activity evoked by words and non-words peaked at equivalent latencies.

This finding stands in contrast to Cohen et al. (2008), who failed to find predicted effects of length over similar areas. The difference in findings between the present study and that of Cohen et al. (2008) may be both task- and stimulus specific. The present study used parafoveally-presented 4- and 8- letter words in a lexical decision task whilst ERPs were recorded. Cohen used 4- and 6- letter words in a silent naming task that recorded fMRI responses. Firstly, it may be the case that the length difference in Cohen et al's. (2008) study (i.e. just 2 letters) was insufficient for an effect to be detected. Secondly, it may also be the case that the high temporal resolution of the ERP measures used in the present study was more suited to detecting hemisphere-dependent length effects than fMRI. Finally, the stimuli presentation in Cohen et al's (2008) study always overlapped the fovea to some degree, whereas in the present study, stimuli were always presented parafoveally. Thus, these differences in terms of task and stimuli may explain why the present study found the predicted effects whereas Cohen et al. (2008) did not.

Previous research has produced conflicting results as to the effect of laterally-presented words on neural activity at 200ms. For example, Barca et al. (2010) have previously shown that the right visual field advantage commonly observed in behavioural tasks is represented in the brain's activity between 100-300ms. In particular, Barca et al. (2010) found LH responses to contralateral words were larger than those to ipsilateral words between 80-375ms. However, these results were not supported by Cohen et al. (2000), who found LH occipitotemporal responses to LVF and RVF words to be similar on the late N1 component. The present study contributes to understanding in this area by confirming that a hemispheric asymmetry in responses to laterally-presented words is apparent in ERP responses at 180ms, thus supporting the results of Barca et al. (2010). Specifically, the present results indicate that word length evokes differential effects on each of the hemispheres at 180ms, which strongly supports the idea that each of the hemispheres processes words in a different way. One reason the results of Cohen et al. (2000) may conflict with the present study concerns the number of participants involved. In Cohen et al. (2000), analyses were based on the results of five participants. The present study involved a group of twenty-two participants. This may be of importance as, as Barca et al. (2010) note, the data of Cohen et al. indicate a trend for stronger VWFA area responses to RVF-presented targets, although – possibly due to a lack of statistical power – the trend did not reach significance. Thus, the results of the present study constitute the first relatively large-scale investigation of the neural basis of the length by visual field interaction. Furthermore, as both Barca et al. (2010) and Cohen et al. (2000) used pronunciation tasks, the present study contributes to understanding in this area by demonstrating that the interaction of length and visual field is present in ERPs generated in response to lexical decision, a relative 'purer' measure of word recognition than word naming/pronunciation.

Analysis of the effect of length across all time-windows of interest indicates a shifting pattern of hemisphere-dependent and length-dependent effects. Early responses (P1 and N1) were dominated by hemisphere-specific effects and, as such, were strongly affected by the location of the word in the visual field. The location of a target became less important after ~200ms, at which time responses were largely dominated by length-dependent effects. This suggests that, after ~200ms, the position of a laterally-presented word ceases to impact upon its subsequent processing and words are processed independently of where they initially appeared in space. At this time, length exerted its strongest effects (180-280ms and 280-380ms). This is in general agreement with Cohen et al (2000), who found that hemifield-dependent effects waned after 180ms, suggesting that whilst early processing may be carried out in both contralateral hemispheres, from ~180ms, processing becomes centred in the LH, irrespective of the target's initial location.

To ascertain the effect of presenting words in the visual fields, as compared to presenting them centrally, a brief comparison will now be made between the results of the present experiment and Experiment 1. Visual inspection of waveforms from both experiments shows that, in general, responses to laterally-presented words were far smaller than those to centrally-presented words. Thus, it seems that one effect of presenting stimuli laterally is to greatly reduce the size of amplitudes that are observed. In Experiment 1, a time-dependent effect of length was found, consistent with previous research (e.g. Hauk & Pulvermüller, 2004), such that long words generated larger responses early on, whilst shorter words become dominant later in the processing cycle. The results of the present experiment also demonstrate a shifting effect of length, although the pattern of effects seems quite different from those generated by centrally-presented words.

The effect of length changed across the four time-windows of interest. On the P1 component, no length effect was apparent. For the N1 component, length effects emerged separately in each hemisphere, dependent on lexicality, with short items creating larger (i.e. more negative) responses. Between 180-280ms and 280-380ms, the effect of length had shifted and long words now generated largest responses. This is quite different from Experiment 1, where long words elicited larger responses early on and short words become dominant later in the processing cycle. One factor that might explain this is the reduced acuity of laterally-presented targets as opposed to centrally-presented target. Outside the foveal region, acuity drops sharply as distance from fixation increases. This may particularly affect long items, as they extend further into the parafovea. As such, this reduction in acuity for long targets may have cancelled out the increased activity observed for long words and non-words on the P1 components in Experiment 1, resulting in no effect of length on the P1 component in Experiment 2.

In Experiment 1, the N1/170 component demonstrated no length-dependent effects, whilst a length effect at 240-340ms demonstrated larger responses to short words. By contrast the present study showed length effects on the N1 component that varied as a function of hemisphere and lexicality, and a length effect between 180-280ms, during which time long words generated the largest responses. Whilst this may suggest that the shifting, time-dependent effect of length (previously described in Experiment 1) might be of a different nature for laterally-presented words, it may also have occurred due to the differing topographies of waveforms to centrally- and laterally-presented words. This means that the time-windows selected both in the present experiment and Experiment 1 varied, particularly because analyses for laterally-presented words included contralateral and ipsilateral activity, which differ substantially in their timing. This precludes the statistical comparison of activity from the present experiment and Experiment 1.

The present chapter reported the results of the first study to record ERP responses evoked by the presentation of words of various lengths directly to the left and right hemispheres. The findings demonstrated that the previously reported length by visual field advantage - which has been extensively reported in the behavioural word recognition literature and was replicated in the present experiment - is reflected in the ERP response over parietooccipital areas at 180ms. This strongly suggests that each of the hemispheres processes written words in different ways. Furthermore, the present study contributes to understanding in this area as the reliability of using the DVF technique without strict eye-fixation control has been called into question (e.g. Jordan, Patching, & Milner, 1998). The pattern of early ERP responses observed in the present experiment indicated that the DVF paradigm was successful in stimulating the intended hemisphere.

Results of the present experiment have shown that word length affects the hemispheres differentially at 180ms. It has previously been suggested (Bub & Lewine, 1988; Ellis, Anderson, & Young, 1988) that the LH can process words in a fast, whole-word manner which is not available to the RH. Words presented to the RH, and unfamiliar words and letter strings presented to the LH, are assumed to be processed in a more sequential, length-dependent manner. Therefore, while the results of the present study strongly suggest the LH and RH process words in different ways, the following chapter will use words with varying orthographic uniqueness points (OUP) to further explore the style of processing used by each hemisphere.

Chapter 6: Orthographic Uniqueness Point

The presence or absence of a word length effect in visual word recognition has long been at the centre of the debate as to whether reading is a serial or parallel process. Furthermore, it has also been central in exploring the extent to which each of the hemispheres has a characteristic processing mode or style (i.e., parallel in the left hemisphere and serial in the right hemisphere). Another factor that has been used to explore the potential parallel/serial nature of word reading processes is orthographic uniqueness point (Kwantes & Mewhort, 1999). The orthographic uniqueness point (OUP) of a printed word is defined as the letter position at which the word becomes unique and, therefore, distinguishable from all other items in the mental lexicon. For example, the OUP of *acrylic* is 4. This reflects the fact that, when reading from left to right, upon reading the letter *y*, *acrylic* is the only possible remaining match. By the same token, the OUP of ***brother*** is 7 as, at letter position 6, there are still other possible matches (e.g. *brothel*).

The study of uniqueness point effects is rooted in the spoken word recognition literature. The cohort model of speech perception (Marslen-Wilson, 1984) proposes that the onset of a speech signal triggers a real-time search of a listener's mental lexicon for possible matches, which yields a cohort of potential candidates. As more of the speech stream becomes available, the number of cohorts decreases until just one candidate remains. The point in the speech stream at which just one candidate remains is the uniqueness point (UP). Marslen-Wilson (1984) found that the time taken to identify a spoken word is a linear function of the distance between the word's onset and its uniqueness point, with late UP words being recognised slower than early UP words.

The perception of spoken words is fundamentally different from that of printed words, primarily because the speech stream is highly sequential in nature and not all information about the identity of a word is available at onset. As such, the finding that early UP words are identified faster than late UP words is a natural consequence of the distribution of the speech signal across time, meaning that an early UP is always perceived before a late UP. This strongly suggests that speech processing is highly serial in nature.

By contrast, when presented with a printed word, all the information that a skilled reader needs to identify that word is immediately available. As much debate remains as to whether printed words are processed in serial or parallel (see Chapters 2 and 3), clearly, the presence or absence of uniqueness point effects in the recognition of visually-presented words may help to further understanding of how printed words are read. To this end, Radeau, Morais, Mousty, Saerens, and Bertelson (1992) applied the principle of UP to written words. Using stimuli that had previously been shown to elicit robust UP effects in spoken word recognition tasks, Radeau et al. (1992) defined the UP for a printed word as the letter position of the phoneme that uniquely identified the word in spoken word identification tasks. In a set of experiments employing a gender classification task, a naming task and a semantic classification task, Radeau et al. (1992) found no evidence of facilitated processing for early UP words; instead, they found a small but consistent advantage for late UP words. On the basis of this, Radeau et al. (1992) suggested that the identification of printed words was not sequential in nature and was unlikely to operate on a cohort-style model, as posited for the recognition of spoken words (Marslen-Wilson, 1984). However, there are some problems in using a phonological criterion when establishing the uniqueness point of orthographic letter strings. As Kwantes and Mewhort (1999) pointed out, using Radeau et al.'s (1992) definition of UP, *service* and *certain* would be in the same cohort of words as their initial phonemes are identical. However, these two words are visually dissimilar and it is unlikely that, for example, *service* would be a realistic candidate during the recognition of *certain*. Likewise, *chord* and *chore* are visually similar but differ in terms of their initial phoneme. Thus, according to Radeau et al.'s (1992) definition of UP *chord* and *chore* would not be expected to be candidates activated during the visual recognition of one or the other.

To address this issue, Kwantes and Mewhort (1999) redefined the UP on orthographic grounds. As such, the orthographic uniqueness point (OUP) of printed words is defined as the letter position at which only one possible match remains in the mental lexicon. In a word naming task using centrally-presented 7-letter words, Kwantes and Mewhort (1999) found that, on average, early OUP words were named 26ms faster than late OUP words. This effect disappeared under conditions of delayed naming, suggesting that the effect is linked to lexical access rather than response output processes. On the basis of these findings, Kwantes and Mewhort (1999) suggested that visual word recognition proceeds in a highly sequential manner.

Using the same stimuli as Kwantes and Mewhort (1999), Lindell, Nicholls and Castles (2003) sought to address the question of whether word recognition in each of the hemispheres proceeds in a serial or in a parallel manner. In order to do this, they presented 7-letter early and late OUP words to the left and right visual fields using a lexical decision task. Lindell et al. (2003) found a 33ms advantage for early over late OUP words. Critically, this advantage did not differ by visual field, suggesting that both hemispheres were equally affected by the position of the OUP. Error rates did not differ as a function of OUP, although it is worth noting that some of the conditions in Lindell et al.'s (2003) experiment had error rates approaching 50%. On the basis of these findings, Lindell et al. (2003) concluded that both hemispheres process words in a serial manner. These findings were replicated in a follow-up study by Lindell, Nicholls, Kwantes, and Castles (2005), in which they assessed the performance of each of the hemispheres when naming laterally-presented early and late OUP words. Words with early OUP were named faster than words with a late OUP in the LH but not in the RH (Experiment 1). In their Experiment 2, this asymmetry was attributed to the relatively poor perceptibility of the initial letters of words in the LVF, as the OUP effect was observed in both hemispheres when visual acuity was controlled by presenting words vertically.

Thus, the findings of Kwantes and Mewhort (1999) and Lindell et al. (2003, 2005) suggest that early OUP words are recognised and named faster than late OUP words. This pattern was observed whether words were presented centrally or laterally, suggesting that the manner in which word recognition is achieved does not vary between hemispheres and is likely to be highly sequential in nature.

Another commonality exists between the work of Kwantes and Mewhort (1999) and Lindell et al. (2003, 2005). Kwantes and Mewhort (1999) and Lindell et al. (2005) both use the same 100-word set of 7-letter stimuli, whilst Lindell et al. (2003) used a smaller, 60-word subset of Kwantes and Mewhort's original 100-word pool. Thus, the stimuli used in all these experiments were highly similar. The use of identical stimuli is not a problem in itself; however, the stimuli used by Kwantes and Mewhort (1999) have been criticized by Lamberts (2005) as being flawed. Specifically, Lamberts argues that Kwantes and Mewhort's stimuli were not controlled for total lexical overlap, a variable which may be confounded with OUP. Total lexical overlap refers to the number of letters-in-position shared by the target and other words within the lexicon. For example, *house* and *goose* share 3 letters-in-position in common. In a computational analysis, Lamberts (2005) found that Kwantes and Mewhort's early OUP stimuli shared 4 letters-in-position with 19 other words in the database; by contrast, late OUP words shared 4 letters-in-position with 46 other words. Thus, the OUP effects reported by Kwantes and Mewhort (1999) and Lindell et al. (2003, 2005) may have been attributable to the extent to which early and late words overlap with other lexical entries rather than the impact of the position of the uniqueness point itself.

Taking into account the argument of Lamberts (2005), Miller, Juhasz, and Rayner (2006; Experiment 2) used a set of 7-letter early and late OUP words that were matched for a range of lexical variables, including total lexical overlap (i.e. matched in terms of the number of items having 4 letters-in-position in common with the target). Using a sentence reading paradigm, a range of eye-tracking measures were recorded from participants as they read sentences with embedded early and late OUP words. Miller et al. (2006) found no benefit for early OUP words; however, several eye-tracking measures demonstrated a small but consistent advantage for late OUP words. This is the opposite pattern to that observed by Kwantes and Mewhort (1999) and Lindell et al. (2003, 2005) but similar to that of Radeau et al. (1992). As an additional analysis, Miller et al. (2006) submitted their stimuli to the English Lexicon Project (Balota, Cortese, Hutchison, Kessler, Loftis, Neely, Nelson, Simpson, & Treiman, 2007; http://elexicon.wustl.edu/), a database of RT and accuracy measures for lexical decision and word naming. For lexical decision, Miller et al.'s (2006) stimuli generated the same pattern in the ELP analysis as in the eye-tracking analyses – that is, late OUP words were responded to faster than early OUP items.

Thus, the effect of OUP on the recognition of centrally- and laterally-presented words remains unresolved. This may be due to a) the way that OUP has previously been defined and b) failure to control for total lexical overlap. Therefore, the three experiments reported in this chapter use stimuli that defined OUP orthographically rather than phonologically and were matched for a range of lexical variables, including lexical overlap (cf. Lamberts, 2005).

Experiment 3 seeks to establish if an effect of OUP is present for well-controlled, centrally-presented words. A lexical decision task will be used to ascertain the effect of early and late OUP words on RT and response accuracy whilst EEG recordings will explore the neural activity generated by varying the position of the OUP. If words are processed in a sequential manner, it is predicted that responses to early OUP words should be faster and more accurate than those to late OUP words. If words are processed in parallel, early and late OUP words should be responded to with equivalent levels of speed and accuracy. As reviewed in Chapter 2, the N170/N1 ERP component has been shown to be involved in visual word form processing (Brem, Bucher, Halder, Summers, Dietrich, Martin, & Brandeis, 2006). As such, if early and late OUP words evoke differing patterns of electrical activity, it is predicted that these would be evident on the N170.

6.1 Experiment 3

6.1.1 Method

6.1.1.1 Participants

Thirteen monolingual, native English-speaking students (5 male, 8 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 18-25 (mean age: 19) All were rated as strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £15 in return for their participation.

6.1.1.2 Materials

Experimental stimuli were selected from a modified CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). The CELEX database was modified by removing items consisting of more than one word, hyphenated items and words suffixed with –s, –es and –ed. These were removed so that when OUPs were calculated they would not be affected by plurality e.g. *biscuit* would not be compared with *biscuits*. This left 43,371 words for use as potential stimuli. The OUP for each of these words was calculated using a specially developed application (Swansea Orthographic Uniqueness Point (SOUP); Brigham & Wright, 2008). The program loads in the edited CELEX database and calculates the OUP for all words. Potential stimuli can then be identified in a range of ways, including alphabetical order, OUP, word length, by specifying specific letters in specific letter positions (e.g. all words which are 7-letters long and begin *bis*****) and any combination of these factors. The program calculated OUP by sorting all words into alphabetical order and, for any given word, comparing the number of contiguous letters-in-position shared with both the preceding word and the following word. The larger of the numbers plus one was the OUP.

From the stimuli pool, a total of forty 7-letter words were chosen. Half of the words had an early OUP (average OUP letter position: 3.65) and the other half had a late OUP (average OUP letter position: 7). Thus, for words, there were two experimental conditions: (1) early OUP words and (2) late OUP words. All words were matched in terms of frequency, bigram frequency, syllables, lexical overlap and orthographic neighbourhood size. A set of forty 7-letter orthographically legal non-words was also selected from the ARC Non-word Database (Rastle, Harrington, & Coltheart, 2002).

6.1.1.3 Apparatus and procedure

The experiment began with 12 practice trials (6 words and 6 non-words), different from those used as experimental stimuli. Experimental items were presented once the practice trials were over. Participants were exposed to a total of 80 experimental trials (40 words and 40 non-words) upon which they were required to perform lexical decision. Stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 17 inch SVGA display. Participants sat at a viewing distance of 57cm from the display screen in a comfortable chair with a headrest. The experiment was programmed and implemented using E-Prime software (Psychology Software Tools, 2007).

All stimuli were presented in lower-case, Arial font, size 14. Words appeared white against a blue background to minimize screen flicker. Words were presented at fixation and subtended a visual angle of 2˚. The central fixation cross subtended a visual angle of 1°.

Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 180ms at fixation. The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, a message appeared on the screen for 2000ms indicating that their response had been recorded. Immediately after that, the fixation cross was relit for 1000ms as the next trial began. The importance of fixating on the cross during the task was emphasised in the pre-experimental instructions, as was the need for speed and accuracy. Participants were also instructed not to blink during trials. During the practice trials, participants were trained in how to time their blinks such that they occurred after experimental trials.

6.1.1.4 ERP Acquisition and Processing

Acquisition and pre-processing procedures were the same as in Experiment 1.

6.1.2 Results

6.1.2.1 Behavioural Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (4.3% of all trials). Eight percent of responses were participant errors and were rejected from subsequent analyses. Non-words were included in the present experiment so as to make lexical decision possible. As it is not possible to manipulate the OUP of non-words, data for non-words will not be analysed. Mean reaction times, standard deviations and accuracy rates are presented in Table 6.1 for words and non-words.

Table 6.1 Mean response times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of visual field and orthographic uniqueness point. Descriptive data for non-words is also presented (there is no OUP for non-words).

	WORDS	
	Early OUP	Late OUP
M	379	350
SD	172	154
% Acc	78%	87%

	NONWORDS
M	379
SD	142
% Acc	92

Only correct responses were analysed. A repeated-measures ANOVA was conducted on RT data by subjects (F_1), with OUP (early vs. late) as a within-subjects factor. A by-items analysis was also conducted (F_2), with OUP as a between-subjects factor.

6.1.2.1.1 Responses to words

A main effect of OUP was evident in the reaction time data. Words with a late OUP were recognized significantly faster than those with an early OUP: $F_1(1,12) = 8.94$, MSe = 5479.86, $p < .01$, $\eta^2_p = .43$, $F_2(1,38) = 4.41$, MSe = 13816.81, $p < .05$, $\eta^2_p = .10$.

In the analysis by subjects of response accuracy for words the advantage for late OUP words was observed again. By-subjects, late OUP words were recognized more accurately than early OUP words: $F_1(1,12) = 13.45$, MSe = 508.65, $p < .005$, $\eta^2_p = .53$. The by-items analysis showed no main effect of OUP on response accuracy.

6.1.2.2 Electrophysiological Results

Only trials with correct responses were included in ERP analyses. Grand average RMS curves (Figure 6.1), plotted for all conditions across all electrodes, indicated three prominent peaks in the ERP distribution, at ~100ms, ~170ms and ~300ms post-stimulus onset. Due to the fact that the average response time in the behavioural task was 365ms, analyses focused on P1, N170 and P300 components. These components were defined after examining grand average topographies as the maximal positive deflection between 70 and 130 ms (P100), the maximal negative deflection between 160 and 210ms (N170) and the maximal positive deflection between 260 and 330ms (P300) over parietooccipital sites. As in Experiments 1 and 2, analyses were focused on two groups of electrodes, formed from the average of PO3, PO7 and P7 over the left hemisphere and PO4, PO8 and P8 over the right hemisphere.

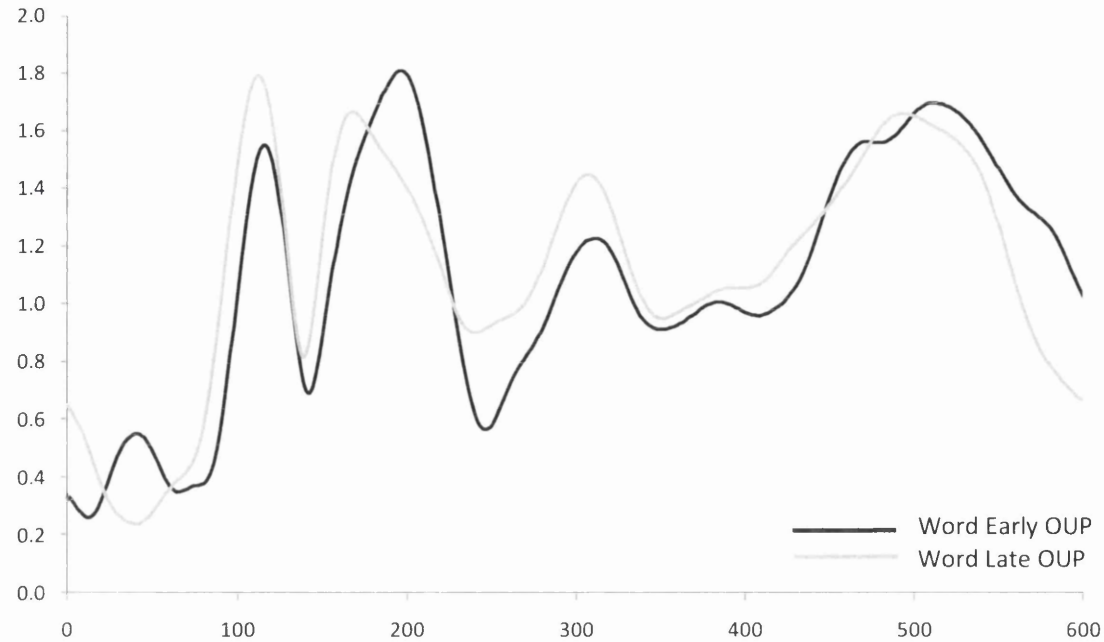


Figure 6.1 Grand mean RMS curves for all conditions plotted across all electrodes, showing three main peaks in the ERP distribution <360ms. *y*-axis is measured in microvolts (μV); *x*-axis is milliseconds.

ERPs were analysed for mean voltage computed across time windows that spanned the peaks of the components of interest. Peak latencies were also computed. For ERPs, two-way repeated-measures ANOVAs were conducted separately on mean voltage and peak latency for ach time-window, with hemisphere (left vs. right) and OUP (early vs. late) as within-subjects factors. All pairwise comparisons are reported using the Bonferroni adjustment to control for multiple comparisons (all $p < .05$ unless otherwise stated).

6.1.2.2.1 Event Related Potentials (ERPs)

Figure 6.2 presents ERP curves for early and late OUP words plotted over the left hemisphere (top panel) and right hemisphere (bottom panel).

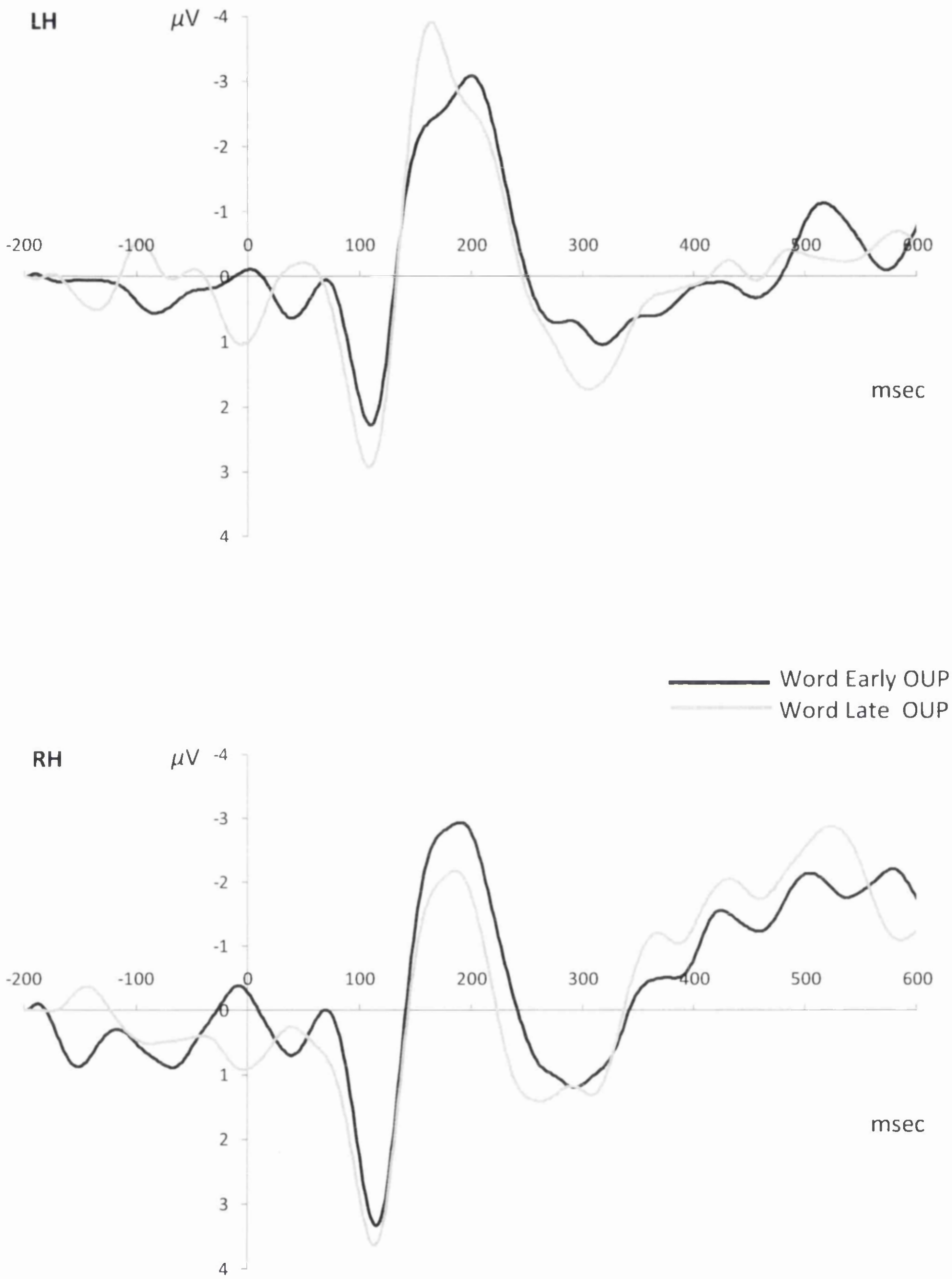


Figure 6.2 ERP curves for early and late OUP words recorded over the LH (electrode group consisting of PO3, PO7, P7) and RH (PO4, PO8, P8). Negative is plotted up.

Figure 6.3 presents topographic scalp maps of the rear of the head for early and late OUP words, for the three time windows of interest.

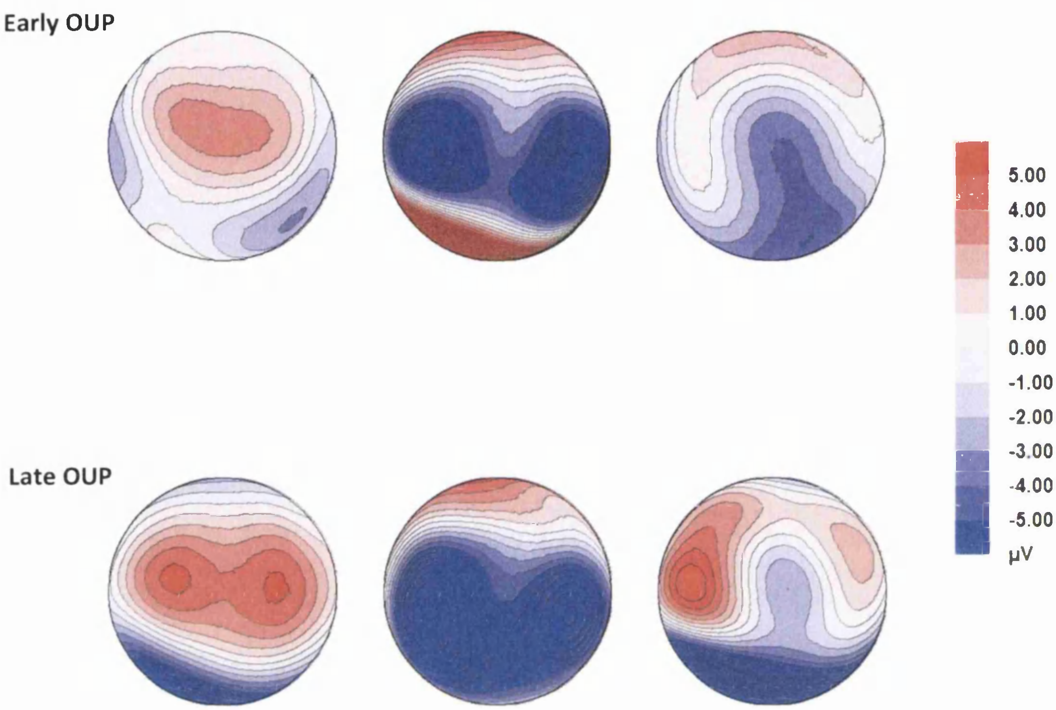


Figure 6.3 Topographic scalp maps of the rear of the head for early and late OUP words.

6.1.2.3 P1 Mean Amplitude and Peak Latency

Amplitudes over the RH were slightly larger than those over the LH, although this effect only approached significance: $F(1,12)=3.48$, MSe = 4.19, $\eta^2_p = .23$, $p = .08$. There was no main effect of OUP [$F(1,12)=3.01$, MSe = 339.22, $\eta^2_p = .20$, $p = .11$] and no interaction of hemisphere and OUP [$F(1,12)= 2.20$, MSe = 446.32, $\eta^2_p = .16$, $p = .16$].

6.1.2.4 N170 Mean Amplitude and Peak Latency

For mean amplitude, there was no main effect of either OUP or hemisphere at 170ms. However, these factors interacted: $F(1,12)=7.84$, MSe = 5.01, $p<.05$, $\eta^2_p = .42$. Bonferroni-corrected post-hoc comparisons indicated that the nature of the interaction was such that early OUP words evoked voltages of equal magnitude in both hemispheres. For late OUP words, amplitudes recorded over the LH (-3.1μv) were significantly more negative than those recorded over the RH (-1.85μv; p = .01). This can be seen in Figure 4.3. There were no main effects in the peak latency analysis. However, as in the amplitude analysis, OUP and hemisphere interacted: $F(1,12)=10.88$, MSe = 961.62, $p<.01$, $\eta^2_p = .50$. In the RH, early and late OUP words achieved peak voltage at similar latencies; in the LH, activity evoked by late OUP (174ms) words peaked significantly faster than that for early OUP words (191ms; p =.02).

6.1.2.5 P300 Mean Amplitude and Peak Latency

No effects were observed on either mean amplitude or peak latency at ~300ms.

6.1.3 Discussion

The aim of the present study was to examine the effect of orthographic uniqueness point on the electrophysiological response. Participants performed lexical decision on centrally-presented letter strings with early and late orthographic uniqueness points whilst EEG recordings were made. Standard behavioural measures of RT and accuracy were obtained, in addition to ERP measures of mean amplitude and peak latency.

The results from the behavioural task are clear: words with a late uniqueness point were recognised faster and more accurately than those with an early uniqueness point. In the ERP analysis, this facilitation was reflected in the LH, where late OUP words achieved peak latency significantly earlier than early OUP words. Across hemispheres, early OUP words generated equivalent activity in both the LH and the RH, whilst late OUP words generated larger negativities over the LH than the RH at 170ms.

The results from the present experiment are consistent with those of Miller et al. (2006) in suggesting that when stimuli are controlled for a variety of lexical variables - including total lexical overlap - there is a consistent advantage for late OUP words over early OUP words. Furthermore, as Miller et al. (2006) employed a sentence-reading paradigm, the results of the current research extend understanding in this area by demonstrating that a facilitatory effect for late OUP words is also found in tasks involving the identification of single words. These findings are contradictory to those of Kwantes and Mewhort (1999), who observed a 26ms advantage for early vs. late OUP words. By contrast, the present experiment found a 29ms benefit for late OUP words over early OUP words. It is likely that the opposing findings of the present experiment and those of Kwantes and Mewhort (1999) are attributable to the way stimuli were matched in terms of lexical variables. Specifically, stimuli in the present research were matched in terms of the extent to which each target shared 4 letters-in-position in common with other words following Lambert's (2005) suggestions. The results of the present experiment show that when word sets are matched for lexical overlap, in addition to other relevant factors, an effect of late OUP words is apparent under conditions of central presentation. An account of left-to-right sequential processing of centrally-presented words would predict faster recognition times for words with an early OUP. Thus, the results of the present experiment cannot be explained by a strictly sequential processing account.

The present study provided the first electrophysiological evidence of an effect of orthographic uniqueness point on neural activity. Early and late OUP words generated distinctly different patterns in each of the hemispheres on the N170 component. The behavioural advantage for late OUP words was reflected in the ERP findings in two ways: firstly, in the peak latency analysis, where, in the LH, late OUP words achieved peak latency significantly earlier than early OUP words and, secondly, across hemispheres, where late OUP words generated larger responses over the LH than the RH. Given that ERP responses to early OUP words were of equal magnitude in both hemispheres, this suggests that the behavioural facilitation for late OUP words may be driven by LH activity.

A serial account of hemispheric word recognition predicted that early OUP words would be recognised faster than early OUP words. This was not the case in the present study, which instead observed facilitated responses for late OUP words. Such a pattern is explainable as the product of an 'ends-in' scanning process. If analysis of the word is based on an 'ends-in' scan, this would mean that a late OUP (which, in this study, would be the last letter of the word) would be perceived before an early OUP (which, in this study, were in the middle of the word). Ends-in scanning has previously been suggested as a form of sequential processing (Bradshaw, Bradley, Gates, & Patterson, 1977; Jordan, Patching, & Milner, 2000; Jordan, Patching, & Thomas, 2003) although it is also compatible with parallel processing models which also find an advantage for outside letters vs. mid-string letters (Ellis, 2004).

The Split Fovea Theory (SFT) offers another possible explanation. Assuming that, for a centrally-presented word, the first half of the word – which falls in the LVF – projects initially to the RH, with the second half – falling in the RVF – projecting to the LH, it is possible that early and late OUPs were initially projected to different hemispheres. In the present experiment, an early OUP fell, on average, in the middle of the string. By contrast, a late OUP – which was always letter position 7 – would fall in the RVF. Thus, it may be the case that early OUP words were received by both hemispheres, as the OUP was at (or very close to) fixation. This is supported by the results of the ERP amplitude analysis, which show that amplitudes evoked by early OUP words were equivalent in both hemispheres. For late OUP words, the OUP was 7 character spaces to the right of fixation, meaning that the portion of the word containing the OUP may have projected directly to the LH only. If this is the case, it could mean that processing of an early OUP, which was possibly projected to both hemispheres simultaneously, may have been hindered due to the involvement of both hemispheres. For example, the word *biscuit*, which has an OUP at letter position 4, may have been split such that *bis**c*** was initially projected to the RH and ***c**uit* to the LH. In this example, each hemisphere would have a copy of the OUP (i.e. ***c***). This duplication may have meant it was more difficult to reintegrate the two halves of the word, a process which presumably takes place in the LH. The ERP data offer some support for this idea, in that, in the LH, early OUP words achieved peak activity significantly later than late OUP words, suggesting a delayed processing for early OUP words, possibly reflecting the difficulty of integrating the two halves of the word which both contain a copy of the OUP.

For a late OUP word, such as *brothe**r***, only the LH should receive a copy of the OUP. This is supported by the ERP data, which showed that late OUP words reached peak activity significantly earlier than early OUP words. Thus, relative to early OUP words (in which case it is possible both hemispheres received a copy of the OUP simultaneously), when the two halves of the word are integrated, the LH only has one copy of the OUP to contend with, facilitating processing and leading to an advantage for late OUP words over early OUP words.

In summary, it was shown that when stimuli are well-controlled for a range of lexical variables – including total lexical overlap – late OUP words are recognised faster and more accurately than early OUP words. This pattern was reflected in the ERP analysis, where late OUP words achieved peak latency significantly earlier than early OUP words. Moreover, the two hemispheres differed in terms of their responses to late OUP words, with LH amplitudes being significantly larger at 170ms than RH amplitudes. This suggests that OUP may differentially affect each of the hemispheres. To further test this, Experiment 4 presented early and late OUP words of different lengths directly to each of the hemispheres using a divided visual field paradigm.

6.2 Experiment 4

Experiment 3 showed a differential effect of OUP on each of the hemispheres. Evidence for hemispheric differences in word processing is also present in other studies, showing that word length has a differential effect on each of the hemispheres (e.g. Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988). These studies have suggested that the RH recognises words in a sequential manner whilst the LH has the ability to access a rapid, parallel-like method of recognition that renders it relatively insensitive to the effects of word length. If each of the hemispheres processes words in a qualitatively different way, it is likely that each would be differentially sensitive to OUP. As such, the aim of Experiment 4 was to investigate the effect of OUP on words of different length in each of the hemispheres using lateralised stimuli presentation. In addition to the 7-letter stimuli used in the previous experiment, the current experiment introduced a set of 4-letter words with late OUP – the OUP being the last letter. A set of 4-letter filler words was used to complete the experimental design, as it is not possible to generate 4-letter words with early OUPs. Therefore, analyses will focus on comparing 4-letter late OUP words, 7-letter early OUP words and 7-letter late OUP words in each of the visual fields. It is predicted that if processing is sequential, as has been proposed for words presented in the LVF/RH, then the position of the OUP within the word would be an important determinant of the speed and accuracy with which words presented to the RH are recognised. Specifically, if processing in the LVF/RH is sequential then a) 4-letter late OUP words should be recognised as fast and as accurately as 7-letter early OUP words (since their OUPs fall in the same position) and b) 7-letter early OUP words should be recognised faster than 7-letter late OUP words. In the RVF however, if processing is more holistic in nature, then all three types of words should be recognised equally quickly and with equivalent levels of accuracy.

6.2.1 Method

6.2.1.1 Participants

Twenty monolingual, native English-speaking students (6 male, 14 female) participated in the experiment. None of the participants had taken part in any of the previous experiments. All participants were students at Swansea University, had normal or corrected-to-normal vision and were between the ages of 18-32 (mean age: 21) All were rated as strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received course credit in return for their participation.

6.2.1.2 Materials

Eighty words and eighty orthographically legal non-words were used as stimuli. Half of the items were four letters in length and the remaining half were seven letters in length. The 7-letter words were those used in Experiment 3. Half of the 7-letter words had an early orthographic uniqueness point (average OUP letter position: 3.65) and the remaining half had a late orthographic uniqueness point (average OUP letter position: 7). For the 4-letter words, half of the words had a late uniqueness point (average OUP letter position: 3.85). As it is not possible to generate enough suitable stimuli for a set of early OUP 4-letter items, a set of 4-letter filler words was used to balance the proportion of long and short words presented in the study. Thus, word length (4 letters/7 letters) and OUP (early/late) were manipulated such that four lists of twenty stimuli each were constructed: (1) 4-letter filler words, (2) 4-letter late OUP words, (3) 7-letter early OUP words and (4) 7-letter late OUP words. All words were matched for frequency (from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993)), number of orthographic neighbours and number of syllables. Items were presented once in the LVF and once in the RVF, such that there were a total of eight conditions for the words used. It is important to note that only six of these conditions were experimental conditions, as the 4-letter filler words included to balance the design were not of theoretical interest and did not form part of the subsequent analyses.

As OUP is a concept that applies only to real words, OUP for non-words could not be manipulated. As such, non-words were included in the preset experiment merely as foils for lexical decision. Accordingly, two lists of non-words were created, each consisting of forty items: (1) 4-letter non-words and (2) 7-letter non-words.

6.2.1.3 Apparatus and procedure

The experiment began with 20 practice trials (10 words and 10 non-words) different from those used as experimental stimuli. Experimental items were presented once the practice trials were over. Each item was presented once in each visual field. Therefore, participants were exposed to a total of 320 experimental trials upon which they were required to perform a lexical decision. Stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 17 inch SVGA display. Participants sat at a viewing distance of 57cm from the display screen in a comfortable chair, with their head in a headrest to maintain head position relative to the screen. The experiment was programmed and implemented using SuperLab Pro (Cedrus Software, 2004).

All stimuli were presented in lower-case, Arial font, size 14. Words appeared white against a blue background to minimize screen flicker. Stimuli were laterally displaced such that the last letter of LVF and first letter of RVF stimuli were 2° from fixation.

Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 150ms, either to the left or to the right of fixation. The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, a message appeared on-screen for 1000ms indicating that their response had been recorded. Immediately after that, the fixation cross was relit for 1000ms as the next trial began. The importance of fixating on the cross during the task was emphasised in the pre-experimental instructions, as was the need for speed and accuracy. The experimental program ordered the stimuli into random blocks of forty items and participants were given the opportunity to take a break after each block of words. Participants recommenced the experiment by pressing a button when they were ready to continue with the experiment.

6.2.2 Results

Response times (RTs) of less than 150ms and more than 2.5 standard deviations from the mean were treated as outliers and removed from further analyses (1.1% of all trials). Sixteen percent of responses were participant errors and rejected from RTs analyses. One participant with accuracy of <60% was discarded and formed no further part in subsequent analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 6.2.

Table 6.2. Mean reaction times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of visual field (LVF vs. RVF), word length (short 4-letter vs. long 7-letter) and orthographic uniqueness point (early vs. late). As there were no Short Early OUP words, data for 4-letter filler words are presented instead. For non-words, M, SD and %Acc are given for length and visual field.

WORDS								
	LVF				RVF			
	Short		Long		Short		Long	
	Filler	Late	Early	Late	Filler	Late	Early	Late
M	588	567	620	627	557	543	603	548
SD	201	172	202	239	237	155	246	162
%Acc	79	79	70	74	84	81	76	84
NON-WORDS								
	Short		Long		Short		Long	
M	660		745		654		728	
SD	239		319		234		266	
%Acc	88		77		84		75	

Only correct responses were analysed. Due to the unbalanced nature of the design (i.e. the lack of early OUP 4-letter words), it was not possible to use an orthogonal analysis combining visual field and OUP factors. Therefore, to compare the three sets of words, a 2x3 repeated measures ANOVA was used with visual field (LVF vs. RVF) and word type (4-letter late OUP, 7-letter early OUP and 7-letter late OUP) as within-subjects factors. Separate analyses were conducted for RT and accuracy, by-subjects and by-items.

Means, standard deviations and response accuracy to non-words are presented in Table 4.2. However, non-word data from the present experiment will not be further analysed. This is because in the context of the present experiment non-words are of limited theoretical interest as it is not possible to manipulate the OUP of non-words. Therefore, non-words merely served as foils to enable lexical decision. As such, the results of non-words from the present experiment will not be reported further.

6.2.2.1 Responses to words

6.2.2.1.1 Reaction Time

RVF-presented words were recognized faster than LVF-targets, by-subjects and by-items: $F_1(1,18) = 12.91$, MSe = 55850.57, $p < .01$, $\eta^2_p = .42$; $F_2(1,53) = 18.95$, MSe = 263.56, $p < .001$, $\eta^2_p = .26$. A main effect of word type was also evident, both by-subjects and by-items: $F_1(2,36) = 5.71$, MSe = 33546.34, $p < .001$, $\eta^2_p = .24$; $F_2(1,53) = 5.81$, MSe = 35536.65, $p < .005$, $\eta^2_p = .18$. Bonferroni-corrected pairwise comparisons showed that four-letter late OUP words (554ms) were recognised significantly faster than 7-letter early OUP words (612ms; $p = .03$). By contrast, 4-letter late OUP words (554ms) and 7-letter late OUP words (593ms) were identified with statistically equivalent speed. Seven-letter early (612ms) and late OUP words (593ms) were also recognised equally quickly.

Visual field and word type interacted significantly by-subjects and marginally by-items: $F_1(2,36) = 6.92$, MSe = 12815.46, $p < .005$, $\eta^2_p = .29$; $F_2(2,53) = 5.81$, MSe = 35536.95, $p < .005$, $\eta^2_p = .18$. This interaction is depicted in Fig. 6.4.

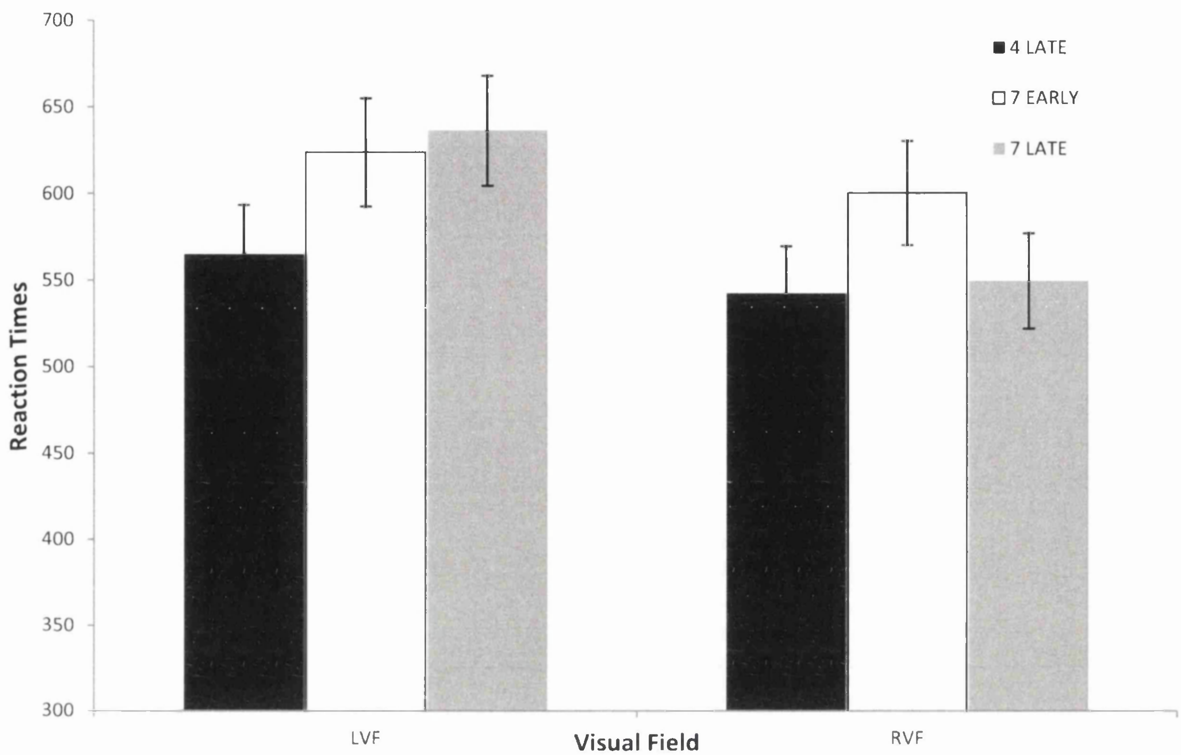


Figure. 6.4 Reaction times to words of varying lengths and uniqueness points as a function of visual field. *y*-axis is in milliseconds.

In the LVF, 4-letter late OUP words (567ms) were recognised faster than 7-letter late OUP words (627ms; p=.02). Seven-letter early OUP words (620ms) were recognised equally as quickly as both 4-letter early and 7-letter late OUP words. In the RVF, 7-letter early OUP words (603ms) were identified reliably slower than both 4-letter late OUP (543ms; p=.04) and 7-letter late OUP words (548ms; p=.009). Four-letter late OUP words and 7-letter late OUP words were recognised equally quickly.

6.2.2.1.2 Accuracy

A main effect of word type was present by-subjects but not by-items: $F_1(2,36) = 5.47$, MSe = 575.67, $p < .01$, $\eta^2_p = .23$; $F_2(2,53) = 5.81$. Responses to 4-letter late OUP words (80%) and 7-letter late OUP words (79%) were equally accurate and both were significantly more accurate than 7-letter early OUP words (73%; p = .023 and p = .016, respectively). By-items, RVF targets (79%) were more accurately identified than LVF targets (73%): $F_2(1,53) = 12.37$, MSe = 825.05, $p < .001$, $\eta^2_p = .19$. The interaction of word type and visual field was not significant by-subjects or by-items: $F_1(2,36) = 1.25$, MSe = 135.63, $p < .30$, $\eta^2_p = .02$; $F_2(1,53) = 2.21$, MSe = 411.25, $p < .71$, $\eta^2_p = .18$.

6.2.3 Discussion

The aim of Experiment 4 was to investigate the effect of OUP on words of different length in each of the hemispheres using lateralised stimuli presentation. Three types of words – 4-letter late OUP, 7-letter early OUP and 7-letter late OUP – were compared in each of the visual fields. It was predicted that if processing in the LVF/RH is sequential in nature, 4-letter late and 7-letter early OUP words would be identified with equivalent speed and accuracy because both sets of words share the point at which they could be identified (fourth letter approximately). Furthermore, 7-letter early OUP words would be predicted to be recognised faster and more accurately than 7-letter late OUP words under a serial processing account. In contrast, if processing in the RVF is more parallel-like in nature, it was expected that all three types of words would be identified with equal speed and accuracy.

The results of the present experiment can be summarised as follows: late OUP words presented in the RVF were recognised faster and more accurately than early OUP words, irrespective of length. In the LVF, words that shared an OUP (i.e. 4-late and 7-early) were identified equally quickly.

Given that presenting words of varying lengths to the RVF typically elicits no effect of length in the LH, the most striking finding of the present study was that a length effect was induced in the LH when comparing 4-letter late OUP words with 7-letter early OUP words. This was contrary to prediction, as it was expected that all three types of words would be recognised equally quickly and accurately in the LH. Thus, it would seem that the LH is sensitive to the relative position of the OUP within a word, with responses to 7-letter words with an early OUP being significantly slower and less accurate than those to both 4-letter late OUP words (which share the same

OUP position) and 7-letter late OUP words (which share the same number of letters). This suggests that, for the LH, it is the relative position of the OUP with a word – rather than the absolute position – that is important, with responses to late OUP words being facilitated relative to early OUP words, irrespective of word length. This supports the findings of Experiment 3, which also found behavioural and electrophysiological evidence for facilitated processing of late OUP words in the LH.

The prediction that all three types of words would be recognised equally well in the LH was made on the basis of previous research that has suggested that the LH may be able to identify printed words in a parallel-like manner (e.g. Bub & Lewine, 1988; Ellis, Anderson, & Young, 1988). Thus, if the LH recognised all the elements of the stimuli in parallel, it was predicted that the three types of words would not differ in terms of response latency and accuracy. The fact that 4-letter late OUP words and 7-letter late OUP were processed at similar speed and accuracy (suggesting an absence of length effect) supports the commonly reported length by visual field interaction, which is often thought to be a marker of LH parallel processing. However, in the present experiment, the fact that 7-letter words with an early OUP were recognised significantly slower and less accurately than other words suggests that the relative position of the OUP does impact upon the recognition of printed words in the LH. This should not be the case if word recognition is "massively parallel" (Howard, 1991), but it is compatible with those parallel processing models that have found an advantage for outside letters vs. mid-string letters (Ellis, 2004).

Thus, the present results are not entirely compatible with the suggestion that word recognition in the LH is entirely parallel in nature. However, due to the pattern of results (i.e. facilitation for late rather than early OUP words), the current findings also do not support a strictly serial, left-to-right account of word recognition. Rather, as there appears to be an advantage for words where the OUP is at or near the end of the string, it may be the case that words in the LH are processed in an 'ends-in' manner. This would mean that a late OUP would be perceived before an OUP in the middle of the word. This account was also supported by the findings of Experiment 3. Ends-in scanning has previously been suggested as a form of sequential processing (Bradshaw, Bradley, Gates, & Patterson, 1978; Jordan, Patching, & Milner, 2000; Jordan, Patching, & Thomas, 2003) although it is also compatible with parallel processing models which also find an advantage for outside letters vs. mid-string letters (Ellis, 2004).

Results from LVF presentation of words are largely supportive of a serial processing account in the RH. Four-letter late OUP words and 7-letter late OUP words demonstrated a clear effect of length and, unlike the LH, were not affected by the fact that they share a relative OUP on the last letter of the string. This suggests a different pattern of processing to that observed in the LH, where the relative position of the OUP within a word strongly affected the speed and accuracy with which words were recognised. Clearly, the fact that 4-late and 7-late words share a relative OUP position (i.e. at the end of the word) did not facilitate the recognition of LVF targets.

In keeping with this, 4-letter late and 7-letter early words (which have the OUP at the same absolute letter position), were recognised with equivalent latencies. This fact that the length effect was extinguished for 4-late and 7-early OUP words strongly suggests that RH processing is sequential in nature and that, moreover, the absolute position of the OUP is a crucial determinant of the recognition of words presented directly to the RH.

In the RH, the comparison of 7-letter early and 7-letter late OUP words demonstrated a non-significant trend for faster responses to early over late OUP targets. Lindell, Nicholls, Kwantes, and Castles (2005) also failed to find evidence of facilitation for early OUP words in the RH during a lateralised lexical decision task. The authors attributed those results to the poor perceptibility of early OUP words in the LVF. In the present experiment, early OUP words had the lowest accuracy rates across both visual fields; however, in the LVF, 7-letter early OUP words were responded to faster than late OUP words (this trend was not significant). Thus, whilst the poor acuity of early letters might play a role in response accuracy, in the present experiment RTs to early OUP words were not disadvantaged relative to late

OUP words. Therefore, it is unlikely that the lack of clear OUP effect for 7-letter words in the RH is attributable to visual acuity issues alone.

Thus, in general, the results of the present experiment are not in agreement with Lindell, Nicholls, and Castles (2003) or Lindell, Nicholls, Kwantes, and Castles (2005), in which facilitation for early OUP words was identified across both visual fields. In contrast, the present experiment found that the hemispheres differed in terms of their sensitivity to OUP, with the LH being strongly affected by the relative position of the OUP within a word, whilst the RH was affected by the absolute position of the OUP within a word. In the LH, responses were facilitated when the OUP fell at the end of a word (rather than at the beginning), irrespective of length. In the RH, responses were faster then two targets shared the absolute position of the OUP (i.e. letter position 4), irrespective of string length. The difference in findings between the present experiment and Lindell et al. (2003; 2005) may be partly due to the nature of the stimuli involved (see Experiment 3 for a discussion of Lindell et al's stimuli and total lexical overlap). Furthermore, the results from the present experiment somewhat replicate those of Experiment 3, which suggested that the LH demonstrated facilitation for late OUP words relative to early OUP words. Taken together, the present results strongly suggest that OUP (and, by consequence, total lexical overlap) are important variables in the study of centrally- and laterally-presented words and may need to be controlled during lexical tasks.

The present results demonstrate that OUP has a differential effect on each of the hemispheres, with the LH being sensitive to the relative position of OUP within a word, and the RH being sensitive to the absolute position of OUP within a word. In particular, the LH shows facilitation for late over early OUP words, regardless of length, whilst the RH length effect can be extinguished when words of differing lengths share an OUP. As reviewed at the start of this chapter, as the size of OUP effects observed can be highly task dependent, it would be valuable to replicate the present experiment with an alternative task. Given that lexical decision may favour holistic over sequential processing, or might introduce some noise due to the presence of the non-words, Experiment 5 will use a word naming task to explore the effects of OUP in each of the hemispheres.

6.3 Experiment 5

The previous experiment demonstrated that OUP has a differential effect on each of the hemispheres when a lexical decision task is employed. To ascertain whether this effect is stable across tasks, a word naming task was employed in Experiment 5. If the pattern of results observed in Experiment 4 is stable across tasks, it is predicted that the LH will show facilitation for late OUP words over early OUP words. In the RH, it is predicted that words that share an absolute position OUP would be recognised equally well.

6.3.1 Method

6.3.1.1 Participants

Twenty-one monolingual, native English-speaking students (8 male, 13 female) participated in the experiment. None of the participants had taken part in any of the previous experiments. All participants were students at Swansea University, had normal or corrected-to-normal vision and were between the ages of 21-35 (mean age: 23). All were rated as strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received course credit in return for their participation.

6.3.1.2 Materials

Stimuli were the same eighty words used in Experiment 4. No non-words were used.

6.3.1.3 Apparatus and procedure

The experiment began with 10 practice trials, different from those used as experimental stimuli. Experimental items were presented once the practice trials were over. Participants were exposed to a total of 160 experimental trials (40 early OUP words and 40 late OUP words, presented once in the LVF and once in the RVF). The participants' task was to name each word aloud as quickly and accurately as possible. Stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 17 inch SVGA display. Participants sat at a viewing distance of 57cm from the display screen in a comfortable chair, with their head in a headrest to maintain head position relative to the screen. The experiment was programmed and implemented using SuperLab Pro (Cedrus Software, 2004).

All stimuli were presented in lower-case, Arial font, size 14. Words appeared white against a blue background to minimize screen flicker. Stimuli were laterally displaced such that the last letter of LVF and first letter of RVF stimuli were 2° from fixation.

Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 150ms, either to the left or to the right of fixation. The participant's task was to name the word presented to them as quickly and as accurately as possible. Participants' responses were registered using a voice key connected to the stimulus presentation computer. As the voice key can be triggered by any vocal sound, in order to check for accuracy, participants' responses were recorded using a digital voice recorder. Once a participant had responded, a message appeared on-screen for 1000ms indicating that their response had been recorded. Immediately after that, the fixation cross was relit for 1000ms as the next trial began. The importance of fixating on the cross during the task was emphasised in the pre-experimental instructions, as was the need for speed and accuracy. The experimental program ordered the stimuli into random blocks of forty items and participants were given the opportunity to take a break after each block of words. Participants recommenced the experiment by pressing a button when they were ready to continue with the experiment.

6.3.2 Results

Response times (RTs) of less than 150ms, more than 2.5 standard deviations and those due to voice-key errors were treated as outliers and removed from further analyses (16.8% of all trials). Three percent of responses were participant errors and were rejected from further analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 4.3.

Only correct responses were analysed. The same types of analyses as those used in Experiment 4 were applied to the results from the present experiment.

Table 6.3. Mean reaction time (M), standard deviation (SD) and response accuracy (Acc%) as a function of visual field (LVF/RVF), word length (short/long) and OUP (early/late).

	LVF				RVF			
	Short		Long		Short		Long	
	Filler	Late	Early	Late	Filler	Late	Early	Late
M	619	654	701	710	609	635	696	653
SD	169	229	233	423	162	194	223	168
%Acc	90	82	77	82	88	84	84	75

6.3.2.1 Responses to words

6.3.2.1.1 Reaction Time

Words presented in the RVF were named faster than those presented in the LVF in the by-subjects and by-items analyses: $F_1(1,20) = 11.51$, MSe = 30512.12, $p < .005$, $\eta^2_p = .37$; $F_2(1,56) = 10.47$, MSe = 24118.48, $p < .005$, $\eta^2_p = .16$. A main effect of word type was found, both by-subjects and by-items: $F_1(2,40) = 10.39$, MSe = 34620.01, $p < .001$, $\eta^2_p = .34$; $F_2(2,56) = 3.28$, MSe = 38195.80, $p < .05$, $\eta^2_p = .11$. Four-letter late OUP words (648ms) were identified significantly faster than both 7-letter early (702ms; $p = .002$) and 7-letter late (690ms; $p = .04$) words. Both sets of 7-letter words were recognized with equal speed.

Visual field and word type interacted: $F_1(1,20) = 10.11$, MSe = 4162.55, $p < .005$, $\eta^2_p = .36$; $F_2(1,56) = 11.98$, MSe = 25548.47, $p < .005$, $\eta^2_p = .25$. Bonferroni-corrected post-hoc comparisons indicated that in the LVF, 4-letter late OUP words (654ms) were named significantly faster than both 7-letter early words (701ms; $p = .01$) and 7-letter late OUP words (710; $p = .02$). In the RVF, 4-letter late OUP (635ms) words were named significantly faster than 7-letter early OUP words (696ms; *p*=.005) but equally fast as 7-letter late OUP words (653ms; *p=ns*).

6.3.2.1.2 Accuracy

No main effect of visual field or word type were found; however, these two factors interacted in the analyses by-subjects and by-items: $F_1(2,40) = 6.02$, MSe = 443.65, $p < .005$, $\eta^2_p = .23$; $F_2(2,56) = 7.76$, MSe = 647.54, $p < .001$, $\eta^2_p = .22$. In the LVF, all word types were named equally accurately. In the RVF, 4-letter late OUP (84%) and 7-letter early OUP (84%) were named with equivalent levels of accuracy. Seven-letter late OUP (75%) words were named with reliably less accuracy than 7-letter early OUP (84%; *p*=.005) words.

6.3.3 Discussion

The aim of the present experiment was to determine the effect of OUP on the naming of words of different lengths presented to the left and right visual fields. It was predicted that if the pattern of results observed in Experiment 4 was stable across tasks, late OUP words would be named faster and more accurately than early OUP words in the RVF. In the RH, it was predicted that responses to words that share an absolute position OUP would be recognised with equivalent levels of performance.

The results of the present study support the predictions in that they are largely in agreement with the findings of Experiment 4 as they indicate a differential effect of OUP on each of the hemispheres. In the LH, the pattern of responses observed mirrored that for Experiment 3, with facilitated responses to words that shared a relative OUP (i.e. on the last letter of the word, irrespective of the length of the word). A length effect was induced in the LH, for the comparison of 4-letter late and 7-letter early OUP words. Thus, the results of the LH strongly support those of Experiment 4 suggesting that the LH is affected by the relative position of the OUP within a target. For the RH, the results were somewhat contrary to prediction and the pattern of responses was slightly different from Experiment 4. In the present experiment, 4-letter late OUP words were named faster than both 7-letter early and late OUP words. There was little apparent influence of the absolute position of OUP, although there was a non-significant trend for 7-letter early OUP words to be named faster than 7-letter late OUP words, again suggesting that RH processing is largely serial in nature. Thus, it may be the case that the influence of OUP on the RH varies as a function of the type of task employed, with lexical decision in the RH being strongly affected by the absolute position of the OUP within a target, and word naming showing less clear effects of OUP.

These results again conflict somewhat with those of Lindell, Nicholls, Kwantes, and Castles (2005). In a word naming task that presented 7-letter early and late OUP words to the left and right visual fields, Lindell, Nicholls, Kwantes, and Castles (2005) found facilitated responses to early OUP words in the LH. In the present experiment, LH facilitation was found for late OUP words, irrespective of word length, supporting the results of Experiment 4 in suggesting that the LH is sensitivity to the relative position of OUP within a word. Lindell et al. (2005) attributed the lack of OUP effect in the RH to be a function of the poor perceptibility of initial letters in the RH. The results of the present experiment do not support this conclusion, as whilst response accuracy was generally better in the RVF than the LVF, of the three word types presented to the LVF, all were recognised with equivalent levels of accuracy. Therefore, it is, unlikely that the lack of OUP effect observed in the RH in the present study is due to low visual acuity of early OUP targets in the LVF.

Experiment 5 sought to replicate the results of Experiment 4 using a word naming task. On the basis of the previous experiment, it was predicted that the LH would be sensitive the relative position of the OUP within a word and the RH would be sensitive to the absolute position of OUP within a word. The results of the present experiment provided strong support for the LH prediction, as, again, words that share an OUP in a relative position (in this case, at the end of a word) were identified equally quickly, irrespective of length. Four-letter late OUP words and 7-letter early OUP words, which share an OUP (in terms of absolute position), demonstrated a length effect. In the RH, the results provided less clear support for the suggestion that the RH is sensitive to the absolute position of the OUP. A standard length effect was found between short words and long words, with no main effect of OUP. However, there was a numerical trend for 7-letter early OUP words to be named faster than 7-letter late OUP words, supporting the contention that RH processing is essentially sequential in nature.

6.4 General Discussion

The present chapter presented three experiments that investigated the effect of orthographic uniqueness point on the recognition of centrally- and laterally presented words. In Experiment 3, early and late OUP words of 7-letters in length were presented in the central visual field whilst electrophysiological recordings were made. Experiment 4 sought to establish the effect of OUP on each of the cerebral hemispheres by using a lateralised lexical decision task and words of different length. Experiment 5 replicated Experiment 2 using a word naming task.

Taken together, the results of the three experiments presented in the present chapter suggest a consistent advantage for late OUP words over early OUP words. This was the case in Experiment 3, where behavioural data indicated that centrally-presented late OUP words were recognised faster and more accurately than early OUP words. The difference between early and late OUP words was evident in the ERP analysis, where the two types of words differed in the pattern of responses on the N170 component. Experiments 4 and 5 both demonstrated an advantage for late OUP words over early OUP words in the LH, regardless of length. It was suggested that this advantage for late OUP targets in the LH may be indicative of an 'ends in' scanning process, which would mean that a late OUP would be perceived before an early OUP. It seems to be the case that, relative to a mid-string OUP, responses to words where the end of the word and the OUP coincide are facilitated in the LH.

In general, the results of the present experiments support the findings of Miller, Juhasz and Rayner (2006), in finding an advantage for late over early OUP words. As such, this reverse OUP advantage has now been demonstrated in sentence reading and eye-tracking measures, in electrophysiological recordings and in lateralized lexical tasks including lexical decision and word naming. The discrepancies between the results of the present set of experiments and those of Lindell et al. (2003; 2005) are largely attributable to a more strict control, in the present study, of lexical overlap across experimental conditions (Lamberts, 2005). Thus, it seems that when the number of shared letters-in-position is controlled, a reliable reverse OUP effect emerges across a range of tasks and using a variety of measures.

The overarching aim of the present experiments was to use OUP as a way to further delineate the type of processing that occurs in each of the hemispheres during visual word recognition. Specifically, it was aimed at testing the idea that the LH is able to process words in a rapid, parallel-like manner, whilst the RH engages a more sequential mode of processing. Studies that have manipulated the length of words presented to the left and right visual fields tend to show a greater effect of length in the RH than the LH, a finding that is generally taken as evidence that the two hemispheres use different modes of processing to recognise printed words. The present study contributes to understanding in this area by confirming that the two hemispheres respond in different ways to the orthographic uniqueness point of words. Experiment 3 demonstrated facilitated behavioural responses to centrally-presented, late OUP words that, on the basis of the ERP data, arose a consequence of LH processing. Experiment 4 confirmed the sensitivity of the LH to OUP and extended this by showing that the relative position of the OUP within a word – rather than the absolute position – was important to LH processing of words. Experiment 5 confirmed this pattern in a word naming task, demonstrating that the effect is stable across tasks. Taken together, the three experiments presented in this chapter offer the first substantial evidence of the neural basis of the OUP effect, which, when stimuli are appropriate controlled, results in facilitation for late over early OUP words. The locus of this effect was shown to be the LH. Directly presented targets to each of the hemispheres permitted further delineation of the OUP effect, showing that, in a lexical decision task, each of the hemispheres is differentially affected by OUP. In particular, the LH is sensitive to the relative position of the OUP within a word. This is in line with an 'ends-in' scanning explanation, which would mean a late OUP is perceived before an early OUP. By contrast, under lexical decision, the RH was shown to be more sensitive to the absolute position of OUP within a word, although this effect was absent during word naming. Nonetheless, Experiments 4 and 5 both suggested strong serial effects in the RH, further supporting the idea that both hemispheres recognised words in qualitatively different ways.

Chapter 7: The influence of Orthographic Depth and Reading Direction on the length by visual field interaction

Does the length by visual field interaction for English words arise as a consequence of the fact that English is read left-right across the page? The question of how reading direction affects visual field asymmetries in visual word recognition has long been of interest (e.g. Melville, 1957), and with good reason. If the right visual field advantage in the processing of words of different lengths is a function of reading direction, a simple, testable prediction can be made: left-right languages should demonstrate a right visual field interaction and right-left languages should show the opposite pattern - that is, a *left* visual field advantage. This is a question of some importance, as, if visual field effects are modulated by reading direction, then it is unlikely that the length by visual field advantage is driven purely by the LH's superior processing style, as has previously been proposed (e.g. Bub & Lewine, 1988; Ellis, Young & Anderson, 1988). Surprisingly, evidence to confirm or reject the reading direction prediction has been remarkably mixed. The purpose of the present chapter is to review those studies that have manipulated reading direction in lateralised word recognition paradigms, with particular reference to the Hebrew language, which is read from right to left. In addition, given that the previous chapter demonstrated the effect of an orthographic variable (i.e. OUP) on the length by visual field interaction, the influence of another orthographic variable – orthographic depth – will be outlined. Orthographic depth (Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992) can be defined as the consistency with which the orthography of a given script reflects its phonology. Thus, in the present chapter, Hebrew is of particular interest as not only is it read from right to left but it also has two written forms that vary in terms of orthographic depth.

7.1 The influence of reading direction

There is evidence to suggest that the reading or scanning direction associated with a given script can influence the perpetual recognition of words and letters printed in that script. This has been investigated looking at the perceptual span difference in reading. Perceptual span can be defined as the visual angle within which the human eye has vision sharp enough to read text. In the context of reading, perceptual span is usually measured as the number of characters to the left and to the right of a single fixation point that can be extracted in a single fixation. Findings from eye-tracking studies have shown that the perceptual span is not symmetrical around the fixation point and is, instead, influenced strongly by reading direction. For readers of left-right languages (such as English, French and Dutch), it has been shown that the perceptual span extends 3-4 character spaces to the left of fixation and 14-15 character spaces to the right of fixation (McConkie & Rayner, 1975). For Hebrew – which is read right-left – the opposite pattern is observed, with a small span to the right of fixation and a larger span to the left (Pollatsek, Bolozky, Well, & Rayner, 1981). Thus, it would seem that the reading direction associated with a given script influences the perceptual span such that a larger span of characters can be perceived from the fixation point towards the end of the word – that is, in the direction of reading.

7.2 Optimal Viewing Position

The speed and success with which a centrally-presented word can be recognised is highly dependent on the letter position fixated within the word. O'Regan, Lévy-Schoen, Pynte, and Brugaillère (1984) have shown that, for words of a left-right script that are between 5- and 11-letters in length, an optimal viewing position (OVP) effect exists such that the speed and successful recognition of a target is highest when readers fixate a point between the first and middle letter of a word. When this happens, the bulk of a word's length falls to the right of fixation, commensurate with the larger rightwards perceptual span for readers of left-right languages.

If the OVP is influenced by reading direction, readers of right-left scripts should show a reversed pattern to left-right readers – that is, they should show a tendency for the OVP to fall at the *right* of a word. Nazir, Ben-Boutayab, Decoppet, Deutsch, and Frost, (2004) found evidence for just such a reversal. In a letter report task, accuracy for both Hebrew and English was always optimal between the beginning and centre of a word, meaning that, due to the difference in reading direction, Hebrew demonstrated an OVP at the right of a target word and English at the left. These findings are supported by eye-movement studies of natural reading, where readers of left-right scripts tend to fixate a point to the left of a word's centre (Nazir, O'Regan, & Jacobs, 1991), whilst readers of right-left scripts tend to fixate a point to the right of a word's centre (Deutsch & Rayner, 1999).

A full discussion of the OVP effect is beyond the scope of this thesis. However, for the present chapter, it is noted that reading direction has been shown to strongly influence the manner in which printed words are read.

7.3 Hebrew Language

Hebrew is of central interest to the present chapter as it is read right-left across the page. We now briefly review some of the fundamental properties of the Hebrew language and outline studies that have made use of Hebrew in studies of lateralised word recognition.

The Hebrew alphabet consists of 22 letters that represent consonants. Most words in Hebrew are formed from consonantal root patterns – most commonly consisting of three consonants – into which vowel information is inserted using a system of diacritical marks. These marks – more commonly known as *points* – can be inserted above, below or between consonants. Thus, a *pointed* word is one in which vowel information is available to the reader and, as such, the full phonological form of the word is specified. By contrast, an *unpointed* word consists largely of consonants without vowel information. Due to its morphological structure, an unpointed word may be ambiguous when read in isolation, as the lack of vowel information means that many unpointed words are homographs. Unpointed script is the most common form of written representation, being used for most books, newspapers and in everyday writing. Children are taught to read using pointed script and it is also commonly found in prayer and poetry books.

As such, written Hebrew can be represented in two distinct ways. Pointed text, in which phonology is accurately represented in orthography, contains all the information a reader needs to achieve a correct pronunciation. By contrast, unpointed words demonstrate a less clear relationship between a word's written and spoken form.

7.4 Orthographic Depth

The regularity with which a script's phonology is represented in its written form is often referred to as *orthographic depth*. Orthographic depth refers to the consistency with which printed words reflect the phonology of their spoken forms, and is typically measured at the language level. English, for example, has relatively inconsistent spelling-to-sound mappings and is considered to be orthographically deep (or opaque). By contrast, languages such as Welsh, Spanish and Italian have a high degree of consistency between their spoken and written forms and are considered to be orthographically shallow (or transparent). Hebrew, having two forms of written representation that vary in the transparency with which sounds are represented in print, has a transparent form (pointed) and an opaque form (unpointed).

The 'depth' of English likely stems from a number of sources, including: (a) The number of irregular words within the language (e.g. *mint*, *pint*; *height*, *weight*); (b) The presence of homophones (*hair*, *hare*) and homographs (for example, *row*, as in an argument and *row*, as in to propel a boat using oars); and (c) the fact that just five vowel letters represent approximately 20 vowel phonemes (Share, 2008). Thus, for a skilled reader of English, successful identification of a printed word is not always achievable on the basis of a rule-based, letter-by-letter decoding procedure as such a procedure would often give rise to an incorrect pronunciation. By contrast, a skilled reader of a transparent orthography is able to apply the highly-consistent spelling-sound correspondences of the language to achieve correct pronunciation of unfamiliar words and non-words.

7.4.1 The Orthographic Depth Hypothesis

The orthographic depth hypothesis (ODH; Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992) proposes that the difference in orthographic depth between deep and shallow orthographies is reflected in the reading strategies employed by readers of the respective languages. In particular, it is suggested that deep and shallow orthographies differ in the extent to which they use lexical (i.e. whole-word based) and sub-lexical (i.e. sub-word units, e.g. individual letters, bigrams, etc) strategies during the recognition of printed words. Specifically, the ODH suggests that readers of shallow orthographies, who are able to make efficient use of the highly regular spelling-sound relationships of their language, may make greater use of sub-lexical mechanisms than readers of highly inconsistent orthographies, who, in turn may rely more on a whole-word based lexical look-up procedure. Thus, the ODH proposes that a form of orthographic efficiency develops during reading acquisition. In shallow languages, in order to generate speech from print, it is most efficient to learn the sounds of small, sub-word units (such as words and bigrams), along with rules for their combination and pronunciation. For deep languages, readers become more attuned to larger sub-word units (e.g. rimes), as reliance on individual letters or bigrams, which are prone to inconsistency, may not generate the correct pronunciation (Ziegler & Goswami, 2005). In each case, the reliance on either the lexical or sub-lexical mechanism appears to be the most parsimonious way to identify printed words in deep and shallow orthographies respectively.

Thus, shallow orthographies assumed to promote sublexical reading are more likely to rely on a sequential-type of processing. By contrast, deep orthographies may depend more on strategies that use relatively large sub-word or whole-word units, yielding a more parallel-like manner of processing. To investigate this possibility, Ktori and Pitchford (2008) used a cross-language task to compare letter search performance in a group of Greek/English bilinguals (Greek being an orthographically shallow language) with that of monolingual English participants. When identifying letters of centrally-presented strings across five letter positions, both bilinguals and monolinguals demonstrated facilitated performance for initial and final letters when the target was an English word. This suggests that, for English words, both groups of participants processed words in a parallel-like manner. By contrast, when recognising Greek words, bilinguals showed a monotonic decrease in performance across the letter string, with facilitation of performance for the initial but not the final letter. On the basis of this, Ktori and PItchford (2008) suggested that Greek words were recognised in a more sequential manner, with performance decreasing left-to-right across the letter string. This supports the idea that orthographically shallow and deep languages may be read best by using qualitatively different strategies.

Assuming that deep and shallow orthographies differ in terms of their reliance on lexical and sub-lexical recognition strategies, it might be the case that the impact of word length on shallow versus opaque languages (and/or scripts) may also be different. As previously discussed, word length is assumed to have a larger effect when processing is sequential than when it is more parallel-like in nature (e.g. Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988). To investigate this possibility, Ziegler, Perry, Jacobs, and Braun (2001) presented words of different lengths to skilled readers of German (a shallow orthographic language) and English. The effect of word length was found to be larger in German than in English. This was attributed to the fact that German reading relies heavily on a sub-lexical strategy that exploits small sub-word units and the longer the word, the more sub-word units need to be processed. This results in a larger effect of length for German than English words, as English words are recognised on the basis of larger units and hence are less prone to the effects of word length.

Thus, orthographic depth has been shown to influence the effect of word length for centrally-presented words. However, the influence of orthographic depth in each of the hemispheres remains unclear. This point will be addressed later.

7.4.2 Visual field asymmetries and reading direction

Early studies of visual field asymmetries in right-left languages demonstrated a left visual field advantage. For example, Mishkin and Forgays (1952) presented English and Yiddish words to the left and right visual fields of Yiddish-English bilinguals

(Yiddish being read right-left). A RVF was evident for English words and a clear LVF advantage for Yiddish words. In a similar vein, Orbach (1967) compared the performance of Yiddish/Hebrew speakers on laterally-presented words in their two languages. In both cases, accuracy was better for LVF presentation although, due to the inclusion of left-and right-handed participants, Orbach was unable to rule out handedness as a factor. Clearly, findings of a LVF advantage in the recognition of laterally-presented words that are from a right-left script strongly suggest that visual field asymmetries are related to reading direction and, as a consequence, may not simply be a function of hemispheric dominance.

More recently, studies have found a RVF advantage for Hebrew analogous to that typically observed for English. Lavidor, Babkoff, and Faust (2001) presented Hebrew words to the left and right visual fields for lexical decision. For horizontal words, a clear RVF advantage was indicated, showing an effect of length in the LVF but not the RVF. Similarly, Lavidor, Ellis, and Pansky (2002; Experiment 2) presented upper-, lower- and mixed-case Hebrew words of 3, 4 or 5 letters in length to each of the visual fields. Mixed case words demonstrated a length effect in both visual fields; however, for both lower and upper case words, a clear RVF advantage was apparent, showing an effect of word length in the LVF but not the RVF. Thus, such studies support the view that the RVF advantage is dependent on cerebral dominance for language and that reading direction exerts little – if any – influence on the nature of the asymmetries observed.

Finally, it should be noted that some studies have reported reduced and/or absent visual field asymmetries for right-left scripts. For example, Babkoff, Faust, and Lavidor (1996) found an overall RVF advantage for Hebrew words in a lexical decision task but no effect of word length in either hemisphere. Babkoff et al. (1996) attribute this finding to the structure of Hebrew words and suggest it is likely that increasing word length in Hebrew elicits different effects to increasing word length in English. Finally, Melamed and Zaidel (1993) presented Farsi/English bilinguals with laterally-presented words for lexical decision and word naming. For English words, performance was better in the RVF than the LVF for lexical decision, reflecting the classic RVF advantage. For Farsi – which is read right-left – no visual field effects were apparent in either lexical decision or naming. Such a finding is problematic for both the hemispheric dominance and the reading direction accounts of visual field asymmetries, as neither fully account for the findings of Melamed and Zaidel (1993).

All the studies reported thus far that have employed Hebrew as a language of interest have either a) used unpointed script or b) not reported the type of script employed. To date, just one study has compared the lateral recognition of pointed and unpointed scripts in Hebrew. Koriat (1985) manipulated the length of words (2-5 letters) in pointed and unpointed script presented to each of the visual fields in a set of experiments. Koriat's (1985) Experiment 1 presented pointed and unpointed words for lexical decision. Only accuracy data are reported. No effect of either word length or visual field were apparent on accuracy, although responses to unpointed words were more accurate than those to pointed words and the presence of pointing was slightly more detrimental to the LH than the RH. In a second experiment, Koriat (1985) replicated Experiment 1 using a pronunciation task, in which pointed and unpointed items were interleaved. A RVF advantage was identified but no effect of pointing was evident on naming latencies. A third experiment, using blocked presentation, replicated the findings of Experiment 2.

One problem with the results of Koriat's (1985) Experiment 1 is that no reaction time data are reported. Thus, although Koriat (1985) report no visual field or length-related effects in the recognition of pointed and unpointed words, it may be the case that any such effects may be evident in participants' response latencies.

7.5 Summary

The present chapter drew together two strands of research - that of reading direction and orthographic depth – and discussed the manner in which each may influence the perception of printed words. In doing so, it was shown that findings that have manipulated reading direction as a means of determining whether the RVF advantage has a cerebral or perceptual basis have provided mixed results, particularly in respect of the interaction of length and visual field. Furthermore, in respect of orthographic depth, it was shown that scripts that vary in orthographic depth may vary in terms of the strategy via which they are best read, which may, in turn, influence the presence or absence of a length effect.

The Hebrew language is ideal for studying both the influence of reading direction and orthographic depth because it is read from right to left and has two forms of written representation. In its pointed form, Hebrew is orthographically transparent; in its unpointed form, Hebrew can be considered orthographically opaque. No study to date has explored both of these factors in a task in which reaction time and response accuracy are measured. In order to further explore the influence of orthographic depth and reading direction in hemispheric word recognition, Experiment 6 presented short and long pointed and unpointed words to the left and right visual fields of native Hebrew speakers. If reading direction is the locus of the interaction of length and visual field, it is predicted that both scripts would demonstrate a LVF advantage. A RVF advantage for both scripts would be predicted if hemispheric dominance accounts for visual field asymmetries. Furthermore, if orthographic depth differentially affects the hemispheres, it is predicted that both hemispheres would show length effects for pointed script but that only the RH will be sensitive to length differences for unpointed script.

7.6 Experiment 6

7.6.1 Method

7.6.1.1 Participants

Twenty two native Hebrew-speaking undergraduates and postgraduates at Bar Ilan University, Israel (5 male, 17 female) participated in the experiment. All participants had normal or corrected to normal vision and were between the ages 20-45 (mean age: 26). All were rated as strongly right handed by a Hebrew version of the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received course credits in return for their participation.

7.6.1.2 Materials

The materials used in this experiment comprised 160 words and 160 legal non-words. Half of the words and half of the non-words were 3 letters in length, with the remaining half of each set being 5 letters in length. Forty of the words and non-words of each length were presented with diacritical marks, whilst forty were presented without. Thus, word length and presence of diacritical marks were manipulated orthogonally such that four sets of words and four sets non-words of forty items each were constructed: 3-letter pointed words, 3-letter unpointed words, 3-letter pointed non-words, 3-letter unpointed non-words, 5-letter pointed words, 5-letter unpointed words, 5-letter pointed non-words and 5-letter unpointed non-words. All word sets were matched for frequency (mean: 3.6 per million words; Hebrew Word Frequency Database, Frost, 2007).

7.6.1.3 Apparatus and procedure

Each experimental session began with 16 practice trials (8 words and 8 non-words) different from those used as experimental stimuli but maintaining the same string lengths (3-letters and 5-letters). Participants were instructed to decide if the item on screen was a real or an invented word. Testing sessions were comprised of 320 experimental trials. Stimuli presentation was randomised and was controlled by an IBM Pentium computer, 586 processor with a 17 inch SVGA display. Participants sat at a viewing distance of 50cm from the display screen. The experiment was programmed and implemented using E-Prime (Psychology Software Tools, 2007).

All stimuli were presented in emboldened, upper-case Courier New font, size 18. Words appeared white against a black background. Stimuli were presented either to the left or to the right of fixation. The inner edge of each word was never closer than 2.7° to central fixation at a viewing distance of 50cm. The central fixation cross subtended a visual angle of 1°.

Trials were blocked such that pointed and unpointed words were presented in separate blocks. The order of block presentation was counterbalanced across participants. Each trial commenced with a fixation cross appearing in the centre of the screen for 500ms. For the first trial only, the fixation cross remained on-screen for 2000ms, to enable participants to orient themselves to the centre of the screen after having read the on-screen instructions. After presentation of the fixation cross, target items were presented for 150ms, either to the left or right of fixation. The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a legal Hebrew word or a non-word. Participants indicated their responses by pressing the appropriate mouse button. Half of the participants were instructed that the left button indicated a word response and the right button a non-word response. Response buttons were reversed for the remaining participants. Once a participant had responded, the fixation cross was lit for 1000ms before the next trial began. The importance of fixating on the focus point during the task was emphasised in the pre-experimental instructions, as was the need for speed and accuracy.

7.6.2 Results

Response times (RTs) of less than 150ms and more than 2.5 standard deviations from the mean were treated as outliers and discarded (<1% of all trials). This led to two participants being excluded from subsequent analyses due to excessive anticipatory responses. Error responses (10.5%) were rejected from subsequent analyses. Mean reaction times, standard deviations and accuracy rates are given in Table 7.1. Only correct responses were analysed. For words, four repeated-measures ANOVAs were conducted on the RT and accuracy data separately, by-subjects and by-items. In the by-subjects analyses, type of script (pointed vs. unpointed), word length (3-letter vs. 5-letter) and VHF (LVF vs. RVF) were within-subjects factors. In the by-items analyses, type of script, length and VHF were between-subjects factors.

Table 7.1 Mean RT (M), standard deviation (SD) and percentage accuracy (% Acc) as a function of visual field, word length, pointedness and lexicality

				WORDS			
		Pointed			Unpointed		
		3 Letters	5 Letters	Difference	3 Letters	5 Letters	Difference
LVF	M	729	760	31	721	739	18
	SD	185	194		171	189	
	% Acc	92	89		92	93	
RVF	M	730	763	33	692	730	38
	SD	189	195		186	195	
	% Acc	93	93		93	93	
				NONWORDS			
LVF	M	785	843	58	803	809	6
	SD	185	226		205	206	
	% Acc	90	84		92	93	
RVF	M	790	873	83	804	846	42
	SD	179	234		196	198	
	% Acc	92	76		87	75	

7.6.2.1 Responses to words

7.6.2.1.1 Reaction Time

Lexical decision latencies were significantly affected by word length: F_1 (1,18) = 8.36, MSe = 33576.17, p < .01, η^2_p = .32, F_2 (1,152) = 9.97, MSe = 33793.9, p < .01, η^2_p = .62. Overall RTs to 5-letter words (748 ms) were significantly slower than those of 3-letter words (718 ms).

A main effect of script type was also evident: F_1 (1,18) = 17.36, MSe = 23978.30, p < .001, η^2_p = .50; F_2 (1,152) = 8.25, MSe = 27955.54, p < .005, η^2_p = .51. Unpointed words (721 ms) elicited significantly faster response latencies than pointed words (746 ms). There was no main effect of visual field: [F_1 (1,18) = .54, MSe = 2767.73, p

= .47, η^2_p = .20]. The two-way interactions of script and word length [F_1 (1,18) = .09, MSe = 159.72, p = .76, η^2_p = .12], script and visual field [F_1 (1,18) = 3.98, MSe = 4136.85, p = .61, η^2_p = .04], word length and visual field [F_1 (1,18) = 1.05, MSe = 1044.28, p = .32, η^2_p = .011] were all non-significant, as was the three-way interaction of word length, script and visual field [F_1 (1,18) = .82, MSe = 810.03, p = .38, η^2_p = .010].

7.6.2.1.2 Error scores for words

Accuracy scores demonstrated a main effect of script type by-subjects but not by-items, showing the unpointed words (93%) were rejected with significantly greater accuracy than pointed words (91%): F_1 (1,18) = 5.97, MSe = 158.06, $p < .05$, η^2_p = .25; F_2 (1,152) = 9.44, MSe = 321.15, $p < .05$, η^2_p = .31. There was no main effect of visual field: F_1 (1,18) = .62, MSe = 37.01, p = .44, η^2_p = .02; F_2 (1,152) = 2.03, MSe = 11.12, p = .55, η^2_p = .01. The two-way interactions of script and word length [F_1 (1,18) = .2.87, MSe = 119.90, p = .11, η^2_p = .22], script and visual field [F_1 (1,18) = .06, MSe = 33.15, p = .81, η^2_p = .001], word length and visual field [F_1 (1,18) = .005, MSe = .16, p = .95, η^2_p = .000] were all non-significant, as was the three-way interaction of word length, script and visual field [F_1 (1,18) = .005, MSe = .16, p = .94, η^2_p = .001].

7.6.2.2 Responses to non-words

7.6.2.2.1 Reaction times for non-words

A main effect of visual field was identified by-items and by-subjects: F_1(1,18) = 6.46, MSE = 15036.26, $p < .05$, η^2_p = .26), F_2 (1,152) = 4.95, MSe = 21850.27, $p < .05$, η^2_p = .32) such that non-words presented to the LVF (mean: 819ms) were responded to faster than non-words presented to the RVF (mean: 839 ms). Responses to non-words were significantly affected by non-word length (F_1 (1,18) = 16.42, MSe = 86663.09, $p < .001$, η^2_p = .47; F_2 (1,152) = 24.72, MSe = 109193.37, $p < .01$, η^2_p = .14), with latencies to 3-letter non-words (mean: 805 ms) being shorter than those to 5-letter non-words (mean: 853 ms).

Non-word length and visual field interacted significantly by-subjects but not by-items: $F_1(1,18) = 12.47$, MSe = 10560.72, $p < .005$, $\eta^2_p = .41$). Post-hoc comparisons indicated that a robust word length effect was evident in both visual fields, although increasing word length had a greater impact in the RVF: the mean difference between short and long words was 30ms in the LVF and 64ms in the RVF. Furthermore, the nature of the length by visual field interaction for non-words is such that 3-letter words were responded to with equivalent latencies in both visual fields, whereas 5-letter words were recognised significantly faster in the LVF (mean: 834 ms) than in the RVF (mean: 871 ms; $p = .002$).

Non-word length, visual field and script type interacted by-subjects: $F(1,18) = 4.55$, MSe = 2177.56, $p < .05$, $\eta^2_p = .20$). The nature of this interaction is depicted in Figure 7.1. For pointed non-words, length effects were evident in both the LVF (59ms; $p = .001$) and in the RVF (77ms; $p = .001$). A length effect was also present for unpointed non-words in the RVF (52ms; $p = .005$). However, short and long unpointed non-words were rejected equally quickly in the LVF.

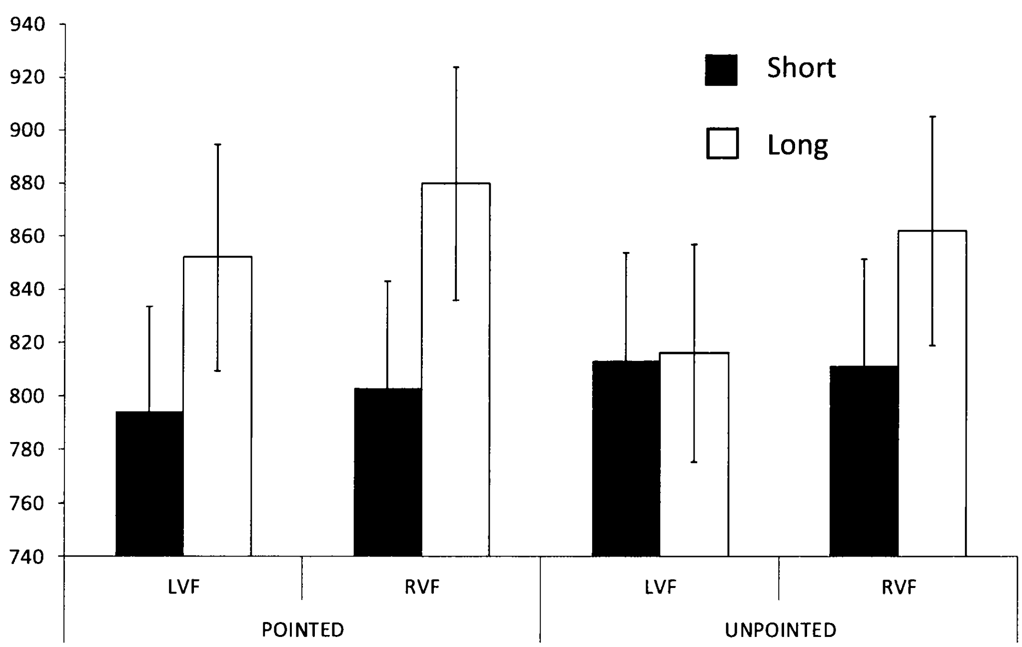


Figure 7.1 Interaction of non-word length, visual field and script type. *y*-axis is measured in milliseconds.

7.6.2.2.2 Error scores for non-words

A three-way repeated measures ANOVA conducted on the accuracy scores for non-words identified a main effect of visual field: $F_1(1,18) = 19.77$, MSe = 1244.90, $p < .001$, $\eta^2_p = .52$; $F_2\,(1,152) = 10.44$, MSe = 1310.42, p < .005; $\eta^2_p = .64$. Responses to non-words presented to the LVF (mean accuracy: 90%) were significantly more accurate than those presented to the RVF (mean accuracy: 84%).

An effect of word length was also evident: $F_1(1,18) = 23.51$, MSe = 2175.16, $p < .001$, $\eta^2_p = .57$; $F_2\,(1,152) = 18.24$, MSe = 2289.65, p < .001; $\eta^2_p = .11$. Short non-words (mean 91%) were recognised with greater accuracy than long non-words (mean: 89%).

Finally, a main effect of script type was present: $F_1(1,18) = 8.90$, MSe = 534.38, $p < .01$, $\eta^2_p = .33$; $F_2\,(1,152) = 4.48$, MSe = 4840.00, p < .05; $\eta^2_p = .29$. Responses to unpointed non-words (89%) were more accurate than those to pointed non-words (85%). The two-way interactions of script and word length [$F_1\,(1,18) = .2.87$, MSe = 119.90, p = .11, $\eta^2_p = .22$], script and visual field [$F_1\,(1,18) = .06$, MSe = 33.15, p = .81, $\eta^2_p = .001$], word length and visual field [$F_1\,(1,18) = .005$, MSe = .16, p = .95, $\eta^2_p = .000$] were all non-significant, as was the three-way interaction of word length, script and visual field [$F_1\,(1,18) = .005$, MSe = .16, p = .94, $\eta^2_p = .001$].

7.6.3 Discussion

The present study employed a lateralised lexical decision task to explore the effects of presenting pointed and unpointed Hebrew words and non-words of varying lengths to the left and right visual fields. The main findings are as follows: for reaction times to words, main effects of word length and script type were present, demonstrating faster responses for short words over long and unpointed words over pointed words. No effects of visual field were observed. For non-words, a clear asymmetry was present such that responses to non-words were faster and more accurate in the LVF than the RVF. An interaction of non-word length, visual field and script type showed that pointed non-words elicited length effects in both visual fields. By contrast, unpointed non-words demonstrated an effect of length in the RVF but not the LVF.

The finding that responses to words demonstrated no visual field asymmetries supports the results of Koriat (1985). Koriat (1985) also manipulated word length and word type in each of the visual fields and reported no effects of word length in terms of response accuracy (the only measure that Koriat (1985) reported). The present study confirms that the lack of visual field effect observed by Koriat in terms of response accuracy is also apparent in lexical decision latencies. Thus, taken together, the results of these studies suggest that the recognition of isolated, laterally-presented Hebrew words does not demonstrate a visual field asymmetry in terms of either accuracy scores of reaction times. Such a finding is problematic for both the reading direction and cerebral dominance account of visual field asymmetries. In terms of reading direction, if the direction in which a script is written influenced the presence of absence of RVF advantage, it was predicted that a LVF advantage would be observed for right-left language. In the present study (and that of Koriat (1985) for Hebrew and Farid & Grainger (1996) for Farsi), no overall visual field effects were observed. This suggests that whilst reading direction may have some influence, it clearly was not strong enough to completely reverse the RVF advantage demonstrated in left-right scripts.

By contrast, if cerebral dominance was solely responsible for the RVF advantage typically observed for English, it was predicted that the same asymmetry would be evidence for LH-dominant (i.e. right-handed) readers of a right-left language. This was not the case in the present experiment; instead, the present experiment identified no overall asymmetry in terms of both reaction time and response accuracy. Again, this does not entirely support the hemispheric dominance view of visual field asymmetries; at most, it suggests that LH dominance for language alone does not drive the RVF advantage observed in left-right scripts and that the balance of any asymmetries between the two hemispheres may be influenced by other factors (such as reading direction).

Results from the present experiment somewhat conflict with those of Koriat (1985) and Babkoff et al. (1996) in that the present work found an effect of length that was evident in both visual fields. In particular, Babkoff et al. (1996) suggested that their lack of main effect and/or any interaction involving length may be due to the structure of Hebrew words, which, in unpointed form, are largely consonantal in nature, meaning that increasing word length may have a different effect in Hebrew than it does to English. Similarly, Koriat (1985) found no effect of length when presenting pointed and unpointed words to each of the visual fields. In both cases, mitigating factors may have prevented the finding of a length effect. In the case of Koriat (1985), only accuracy data are reported; therefore, it is unclear whether a length effect was apparent in reaction times. In the case of Babkoff et al. (1996), the purpose of the experiment was to explore the effect of word rotation on visual field asymmetries. Therefore, it is possible that the effect of rotating words from horizontal may have affected the presence of a length effect.

A main effect of script type indicated that unpointed words were identified faster and more accurately than pointed words in both visual fields. This suggests that both hemispheres were equally affected by the presence (or absence) of pointing.

Results from the non-word analyses show a LVF advantage, with non-words being rejected faster and more accurately in the LVF than the RVF. This is in general agreement with the reading direction account of visual field asymmetries, which suggests that LVF performance should be superior if it has become, through the experience of learning to read, trained in perceiving letter strings in the direction of reading. However, that this effect is present for non-words but not words is not easily explained. Furthermore, an interaction of non-word length, visual field and script type demonstrated that the hemispheres were not equally affected by script type. Pointed non-words induced length effects in both visual fields; by contrast, unpointed non-words only demonstrated a length effect in the RVF. This suggests that the RH was insensitive to the length of unpointed non-words.

The present study showed that, for pointed and unpointed words, length effects occur equally in the two hemispheres. This suggests that both hemispheres use a similar strategy when recognising Hebrew words. By contrast, the hemispheres were differentially affected by non-word type. Thus, based on the results of the present experiment, support for the suggestion that the hemispheres may differ in respect of their sensitivity to orthographic depth is weak, as asymmetries in orthographic depth were observed only for non-words. It may be the case that reading direction mitigated or reduced the effect of this variable in each of the hemispheres. Therefore, in order to further explore the idea that orthographic depth may influence the RVF advantage, Experiment 7 observed the effects of orthographic depth in two languages read from left to right by the same group of speakers. These were: bilingual speakers of English and Welsh.

7.7 Experiment 7

The previous experiment provided inconclusive support for the notion that orthographic depth differentially affects each of the hemispheres. However, the previous experiment also provided little support for either the cerebral dominance or reading direction accounts, given that no clear asymmetry was present and that length effects were observed in both hemispheres. However, it is possible that any effects of orthographic depth may have been mitigated or masked by the effects of reading direction. Thus, in order to further explore the effect of orthographic depth in the recognition of laterally presented words, it would be useful to simplify manipulation of orthographic depth by employing speakers of left-right languages.

English-Welsh bilinguals offer the opportunity to study two levels of orthographic depth within the same speaker. Welsh is orthographically shallow – its sound-spelling mappings are highly regular and a fluent speaker who is familiar with the rules of pronunciation can pronounce unfamiliar and non-words with a high degree of accuracy. As transparent orthographies are thought to rely on a mode of processing that renders them more sensitive to length effects than opaque orthographies (Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992), studies that have explored the effect of word length in Welsh will now be considered.

7.7.1 Word length effects in Welsh

In a developmental study of reading acquisition in Welsh/English bilingual children (Ellis & Hooper, 2001), word length explained more than 70% of the variance in response latencies to Welsh words but just 22% of the variation in responses to English words. This supports the idea that readers of a deep orthography are more likely to read words based on whole-word units and are thus less sensitive to increasing word length. In keeping with this, Spencer and Hanley (2003) examined the reading performance of bilingual Welsh/English and monolingual English-speaking children at age 6. In this study, bilingual children were being educated at a Welsh-medium primary school and lived in homes where Welsh was the dominant language. For English words, there was no association between how well a word was read and its length. In contrast, for Welsh, there was a significant negative correlation between response accuracy and word length, such that performance was poorer for longer words. This again supports the idea that the effect of word length may vary as a consequence of orthographic depth.

7.7.2 Visual field asymmetries in Welsh

Few studies to date have focused on the effect of orthographic depth in each of the hemispheres. In one such study, Beaton, Suller, and Workman (2007) compared Welsh (a shallow orthography) with English. They presented Welsh/English bilinguals and English monolinguals with laterally-presented words for naming. Two groups of bilinguals were recruited: those who had learned English first and those who had learned Welsh first. Each group was further subdivided according to whether the second language had been learned early (before 5-6 years of age) or late (after 5-6 years of age). Bilinguals named English words and their Welsh translation equivalents, whilst English monolinguals named only English words. Word length was not manipulated although was matched across word sets. A laterality index was used as a measure of visual field asymmetry. The laterality index is a ratio which measures the relative bias towards one hemisphere/visual field, with scores ranging from +1 (exclusive RVF/LH bias) to -1 (exclusive LVF/RH bias). Using this measure, Beaton et al. (2007) found a larger right visual field advantage for Welsh than English words in bilinguals, meaning that bilinguals were more biased towards RVF/LH processing. This was true regardless of whether they had learned English or Welsh as their first language or the age of acquisition of their second language. Considering English words alone, monolinguals and bilinguals demonstrated a right visual field advantage that was equal in magnitude. On the basis of these findings Beaton et al. (2007) suggested that the LH is more involved in the recognition of Welsh targets than English targets.

In summary, previous research into orthographic depth suggests that word length may exert differing effects in shallow and deep orthographies (e.g. Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992). This is thought to be due to type of reading strategy favoured by readers of the respective languages, with readers of deep orthographies relying more on whole-word, lexical mechanisms and readers of shallower orthographies preferring a mode of processing that relies more on smaller sub-word units, which necessarily give rise to length effects (Ziegler & Goswami, 2005). As the difference between reading strategies applied to shallow and deep orthographies mirrors the processing styles thought to be favoured by each of the hemispheres (i.e. RH sequential, LH parallel-like), it may be the case that the length by visual field advantage typically observed in lateralised lexical tasks may arise as a consequence of the processing style of the LH matching the optimal strategy for recognising English words. If this is the case, the length by visual field advantage would be specific or more pronounced in languages with an opaque orthography that rely on relatively large sub-word or whole word units for optimal recognition. For shallower languages that cannot take advantage of large unit processing, increasing word length may invoke an effect of word length in both hemispheres.

No study to date has explored the effect of word length on each of the hemispheres of bilingual speakers of a transparent and an opaque orthography. As such, Experiment 7 presented English and Welsh words of different lengths to the left and right visual fields of Welsh/English bilinguals and monolingual English participants. It was predicted that if the effect of length in each of the hemispheres is moderated by orthographic depth then a) bilinguals and monolinguals alike would demonstrate a length by visual field interaction for English words, with an effect of length in the RH but not the LH and b) bilinguals would demonstrate a length by visual field advantage for English but not Welsh, with Welsh demonstrating an effect of length in both hemispheres. As non-words are unfamiliar lexical items and would thus be processed sub-lexically, it was predicted that non-words in both languages would demonstrate length effects in each of the hemispheres.

7.7.3 Method

7.7.3.1 Participants

Twenty monolingual, native English-speaking students (5 male, 15 females) and twenty bilingual English/Welsh-speaking students participated in the experiment.

All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 19-49 (mean age: 34) All were rated as strongly right-handed (>80%) by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £3 in return for their participation. Bilingual participants were given a short questionnaire about their language skills. On average, bilingual participants had been learning their second language (Welsh) since 6 years of age and, on a scale of 1-7 (1 being very low and 7 being as a native speaker), bilinguals rated their reading and listening skills in Welsh as 6 and their writing and speaking skills in Welsh as a 6. All bilingual participants were fluent in both English and Welsh and rated English as their dominant language.

7.7.3.2 Materials

Forty English words and forty Welsh words were used as stimuli. English words were drawn from the Celex database (Baayen, Pipenbrock, & van Rijn, 1995); Welsh words were selected from Fear (1997). Forty legal non-words for each language were also generated by taking a legal word that was not involved in the experiment and changing one letter. Half of the words and non-words for each language were 4 letters in length and the remaining half were 6 letters long. Thus, for each language, there were four experimental conditions: (1) four-letter words, (2) six-letter words, (3) four-letter non-words and (4) six-letter non-words. Both English and Welsh word sets were matched in terms of age of acquisition (English mean: 3.4; Welsh mean: 3.2) and imageability (English mean: 5.7; Welsh mean: 6.0), from the Bristol Norms (Stadthagen-Gonzalez & Davis, 2006) and Fear (1997) respectively. Words were also matched in terms of written frequency from Celex (Baayen, Piepenbrock, & van Rijn, 1993) and Fear (1997) (English mean: 4.6; Welsh mean: 4.3).

7.7.3.3 Apparatus and procedure

All stimuli were presented in Arial font, point size 26. For ease of reading, words appeared as white against a blue background. Stimuli were presented such that the inner edge of words was never closer than 2° to central fixation at a viewing distance of 50cm. The central fixation cross subtended a visual angle of 1°.

Two experimental programs were developed: one using English stimuli and one with Welsh stimuli. Monolingual English speakers completed only the English version of the task; bilingual speakers completed both the Welsh and English tasks. Each program began with 20 practice trials (10 words and 10 non-words), different from those used as experimental stimuli but maintaining the same letter lengths (4-letters and 6-letters). Thus, monolinguals completed 180 trials (20 practice trials and 160 experimental trials) whilst bilinguals completed 360 trials (20 practice, 160 experimental trials each for Welsh and English). Each item was presented once in each visual field. The order in which bilinguals completed the tasks was counterbalanced such that half the bilingual participants completed the Welsh task first, followed by the English task. The remaining bilingual participants completed the tasks in the opposite order. Within each version of the program, the order of stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 15 inch SVGA display. Participants sat at a viewing distance of 57cm from the display screen with their head in a chinrest to maintain head position.

Each version of the experiment began with 20 practice items. Experimental items were presented once the practice was over. Stimuli were laterally displaced such that the last letter of LVF and the first letter of RVF stimuli were 2° from fixation. Participants were instructed to decide if the item on the screen was a real or an invented word as quickly and as accurately as possible. The necessity of maintaining central fixation was also emphasised. Each trial began with a fixation cross appearing in the centre of the screen for 1500ms. When the fixation cross disappeared from the screen, a word was presented either to the left or right of the screen for 150ms. The participant's task was to decide, as quickly and accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing one of two keys on a standard PC keyboard. Half of the participants were instructed that the *P* key indicated a word response and the *Q* key a non-word response. Once a response was made, the fixation cross blinked to let participants know their response had been accepted. The cross remained on-screen for 1000ms, after which time the next trial commenced.

7.7.4 Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (2.9% of all trials). This led to one bilingual participant being excluded from subsequent analyses due to poor accuracy levels (more than 30% errors). Error responses (12.4%) were rejected from subsequent analyses. Mean reaction times, standard deviations and accuracy rates for bilingual and monolingual speakers are presented in Table 7.2.

Table 7.2 Mean Reaction times and % of errors for monolingual and bilingual participants as a function of language, visual field, word length and target lexicality.

		Bilingual speakers						Monolingual speakers		
		WORDS								
		English			Welsh			English		
		Short	Long	Diff	Short	Long	Diff	Short	Long	Diff
LVF	M	550	596	46	612	663	51	493	527	34
	SD	149	244		226	281		153	174	
	% Acc	90	88		87	89		83	81	
RVF	M	527	536	9	575	623	48	470	455	-15
	SD	182	192		242	236		188	162	
	% Acc	92	87		93	87		89	83	
		NON-WORDS								
LVF	M	693	709	16	840	916	76	584	596	12
	SD	274	260		381	399		201	207	
	% Acc	88	88		83	79		83	71	
RVF	M	677	712	35	829	916	87	591	587	-4
	SD	260	273		360	445		217	188	
	% Ac	86	91		82	75		76	80	

Only correct responses were analysed. Two main sets of comparisons were conducted. Firstly, four mixed ANOVAs compared the reaction time and response accuracy of monolinguals and bilinguals by-subjects and by-items when recognising English words. In the by-subjects analyses, linguality (monolingual vs. bilingual) was a between-subjects factor, while word length (short/long) and visual field (LVF/RVF) were within-subject factors. In the by-items analyses word length was a between subject factor while linguality and visual field were within subject. Secondly, the performance of bilingual speakers in each of their two languages was compared using four repeated-measures ANOVA. Here, language (English/Welsh), word length (short/long) and visual field (LVF/RVF) were within-subject factors in the by-subjects analyses, whilst in the by-items analyses, word length and language were between-subjects factors and visual field was a within-subjects factor.

7.7.5 Monolinguals vs. Bilinguals: English words

7.7.5.1 Responses to words

7.7.5.1.1 Reaction Time

Monolinguals identified English words faster than bilinguals, by-subjects and by-items: $F_1(1,37) = 4.81$, MSe = 172752.58, $p < .05$, $\eta^2_p = .12$; $F_2(1,38) = 92.18$, MSe = 176052.78, $p < .001$, $\eta^2_p = .71$. A main effect of visual field demonstrated that responses to RVF were faster than those to LVF by-subjects and by-items: $F_1(1,37) = 41.41$, MSe = 75081.54, $p < .001$, $\eta^2_p = .53$; $F_2(1,38) = 56.81$, MSe = 77922.38, $p < .001$, $\eta^2_p = .60$. A main effect of word length was found in the analysis by-subjects but not in the analysis by items. Thus, short words (510ms) were recognised faster than long words (532ms): $F_1(1,37) = 5.52$, MSe = 17953.86, $p < .01$, $\eta^2_p = .13$.

An interaction of length and visual field was evident by-subjects and by-items: $F_1(1,37) = 11.64$, MSe = 1819.00, $p < .005$, $\eta^2_p = .41$; $F_2(1,38) = 13.77$, MSe = 18885.21, $p < .001$, $\eta^2_p = .27$. The nature of the interaction was such that short words (582ms) were recognised faster than long words (611ms) in the LVF ($p = .001$). In the RVF, short and long words were recognised equally quickly. This interaction is depicted in Figure 7.2. The two-way interactions of linguality and visual field [$F_1(1,37) = 0.00$, MSe = 1819.00, $p < .005$, $\eta^2_p = .000$] and linguality and length [$F_1(1,37) = 1.81$, MSe = 5895.47, $p < .19$, $\eta^2_p = .05$] were non-significant, as was the three-way interaction between linguality, length and visual field [$F_1(1,37) = .05$, MSe = 83.86, $p < .82$, $\eta^2_p = .001$].

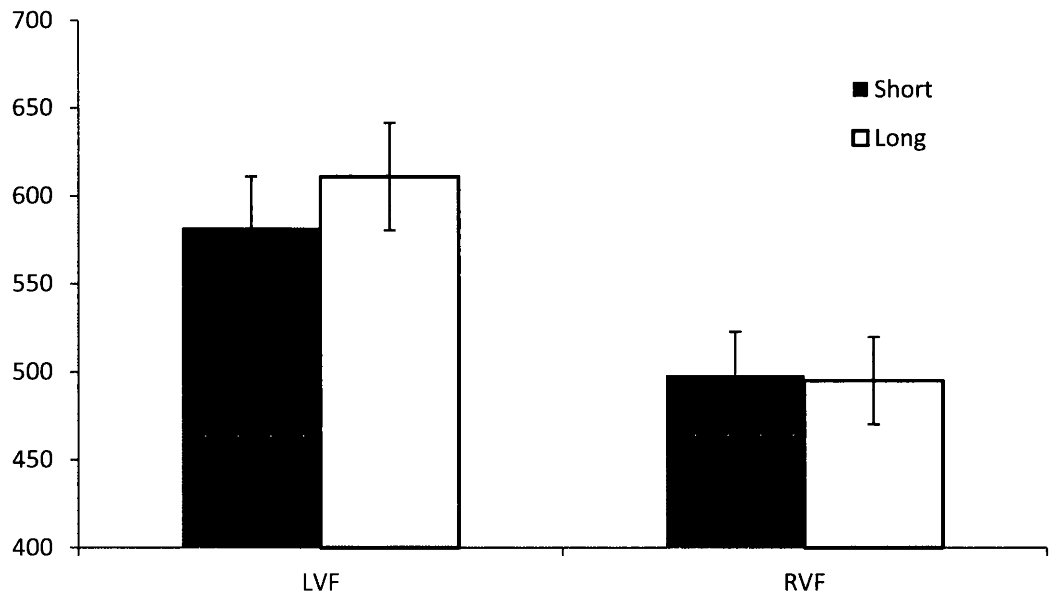


Figure 7.2 Graph of the interaction of word length and visual field, showing an effect of length in the LVF but not the RVF. *y*-axis is in milliseconds.

7.7.5.1.2 Accuracy

Bilingual participants were more accurate at identifying English words than monolinguals: $F_1(1,37) = 6.28$, MSe = 1001.47, $p < .05$, $\eta^2_p = .15$; $F_2(1,38) = 22.58$, MSe = 183918.52, $p < .001$, $\eta^2_p = .23$. A main effect of length was found showing that short words (88%) were recognised more successfully than long words (84%), both by-subjects and by-items: $F_1(1,37) = 9.49$, MSe = 614.39, $p < .005$, $\eta^2_p = .20$; $F_2(1,38) = 8.53$, MSe = 69481.64, $p < .005$, $\eta^2_p = .10$. No other main effects or interactions approached significance.

7.7.5.2 Responses to non-words

7.7.5.2.1 Reaction Time

Monolinguals responded to non-words faster than bilinguals: $F_1(1,37) = 5.00$, MSe = 469202.33, $p < .05$, $\eta^2_p = .12$; $F_2(1,38) = 114.47$, MSe = 471221.69, $p < .001$, $\eta^2_p = .69$. An effect of non-word length was present by-subjects, with short non-words (641) being identified faster than long non-words (652ms): $F_1(1,37) = 4.52$, MSe =

4965.83, $p < .05$, $\eta^2_p = .11$. No other main effects or interactions approached significance.

7.7.5.2.2 Accuracy

Bilinguals recognised non-words more accurately than monolinguals: $F_1(1,37) = 7.70$, MSe = 2498.46, $p < .01$, $\eta^2_p = .17$; $F_2(1,38) = 31.55$, MSe = 2763.91, $p < .001$, $\eta^2_p = .45$. Non-word length and visual field interacted by-subjects and by-items: $F_1(1,37) = 7.12$, MSe = 282.19, $p < .05$, $\eta^2_p = .16$; $F_2(1,38) = 4.22$, MSe = 262.66, $p < .05$, $\eta^2_p = .10$. The interaction, as depicted in Figure 7.3, showed that short words were recognised more accurately in the LVF (84%) than in the RVF (81%; $p = .009$). Long words were identified more accurately in the RVF than in the LVF. No other main effects of interactions approached significance.

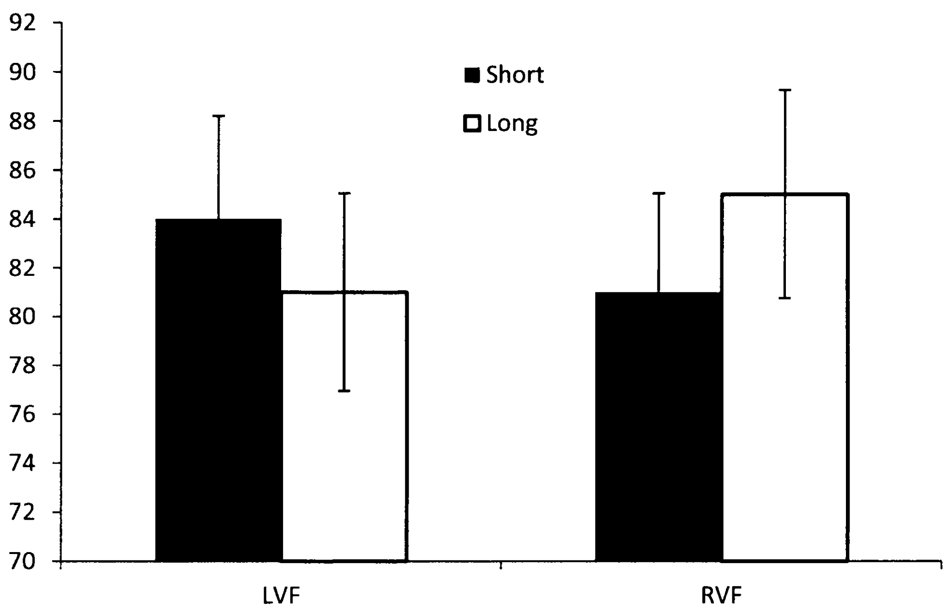


Figure 7.3 Graph of the interaction between word length and visual field. *y*-axis is response accuracy

7.7.6 Bilinguals: English vs. Welsh

7.7.6.1 Responses to words

7.7.6.1.1 Reaction Time

Bilinguals responded to English words faster than to Welsh words, by-subjects and by-items: $F_1(1,37) = 8.09$, MSe = 128628.75, $p < .01$, $\eta^2_p = .31$; $F_2(1,38) = 22.58$, MSe

= 183918.52, $p < .001$, $\eta^2_p = .23$. A main effect of length showed that short words were recognised faster than long words both by-subjects and by-items: $F_1(1,37) = 11.76$, MSe = 75569.85, $p < .005$, $\eta^2_p = .40$; $F_2(1,38) = 8.53$, MSe = 69481.64, $p < .05$, $\eta^2_p = .10$. An effect of visual field was also evident, with responses to RVF targets being faster that to LVF targets: $F_1(1,37) = 16.78$, MSe = 56251.34, $p < .001$, $\eta^2_p = .48$; $F_2(1,38) = 29.47$, MSe = 65278.42, $p < .001$, $\eta^2_p = .28$.

Language, visual field and word length interacted by-subjects: $F_1(1,37) = 4.49$, MSe = 6148.95, $p < .05$, $\eta^2_p = .20$. The interaction is depicted in Figure 7.4. The nature of this interaction was such that, for English, bilinguals demonstrated an effect of length in the LVF ($p = .02$) but not in the RVF. For Welsh, an effect of length was present in both the LVF ($p = .01$) and in the RVF ($p = .001$).

7.7.6.1.2 Accuracy

A main effect of length was found in the analysis by-subjects. Thus bilinguals identified short words significantly more accurately than long words: $F_1(1,37) = 4.55$, MSe = 348.03, $p < .05$, $\eta^2_p = .21$. The interaction between visual field and word length was significant in the analysis by items only: $F_2(1,38) = 5.79$, MSe = 225.63, $p < .05$, $\eta^2_p = .71$. In the RVF, short words (92%) were identified more accurately than long words (87%; $p = .04$). In the LVF, short and long words were recognised equally well. No other main effects or interactions approached significance.

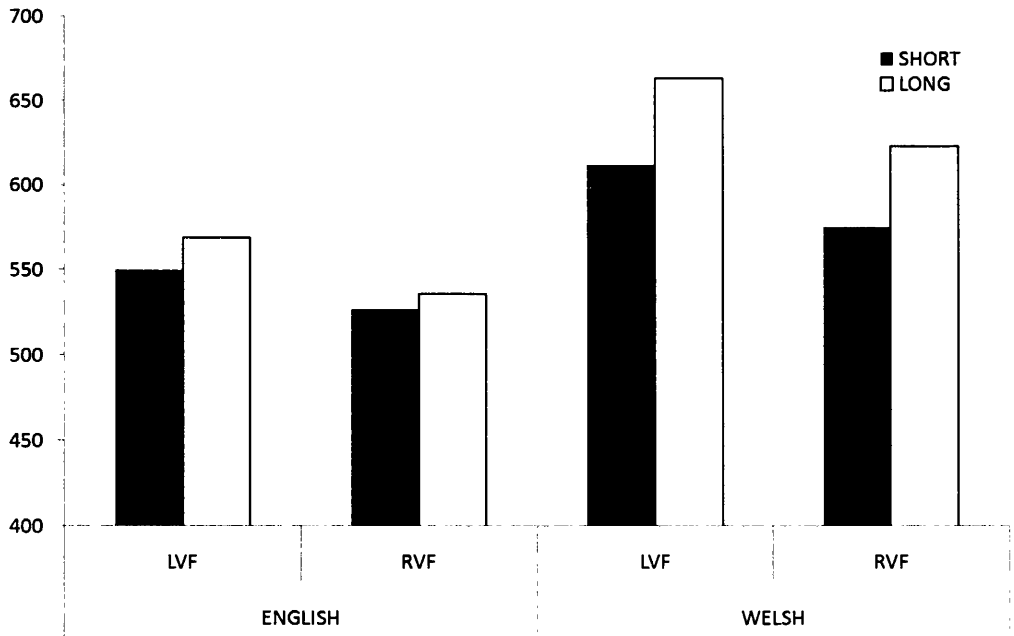


Figure 7.4 Graph of interaction between language, word length and visual field, showing a length by visual field interaction for English but not for Welsh. *y*-axis is measured in milliseconds.

7.7.6.2 Responses to non-words

7.7.6.2.1 Reaction Time

Bilinguals identified English non-words faster than Welsh non-words, by-subjects and by-items: $F_1(1,37) = 22.80$, MSe = 877640.27, $p < .001$, $\eta^2_p = .56$; $F_2(1,38) = 118.57$, MSe = 1268993.89, $p < .001$, $\eta^2_p = .61$. A main effect of non-word length demonstrated that short non-words were recognised faster than long non-words: $F_1(1,37) = 20.35$, MSe = 103962.95, $p < .001$, $\eta^2_p = .53$; $F_2(1,38) = 9.20$, MSe = 98511.53, $p < .005$, $\eta^2_p = .11$. The interaction between language and length was significant by-subjects: $F_1(1,37) = 4.80$, MSe = 45935.89, $p < .05$, $\eta^2_p = .21$, such that, for Welsh, short non-words (810ms) were identified significantly faster than long non-words (897ms; p=.004). This interaction is depicted in Figure 7.5. No significant differences were found between recognition times of short and long English nonwords.

7.7.6.2.2 Accuracy

Bilinguals were more accurate at identifying English non-words than Welsh non-words: $F_1(1,37) = 17.32$, MSe = 1918.42, $p < .001$, $\eta^2_p = .49$; $F_2(1,38) = 8.87$, MSe = 2975.63, $p < .01$, $\eta^2_p = .33$. By subjects, language, non-word length and visual field interacted: $F_1(1,37) = 7.69$, MSe = 168.42, $p < .05$, $\eta^2_p = .29$. The nature of the interaction was such that, for English, long non-words in the RVF (91%) were recognised significantly more accurately than short non-words in the RVF (86%; p = .05). Responses to English non-words in the LVF did not vary as a function of length. For Welsh, responses did not differ by visual field or non-word length.

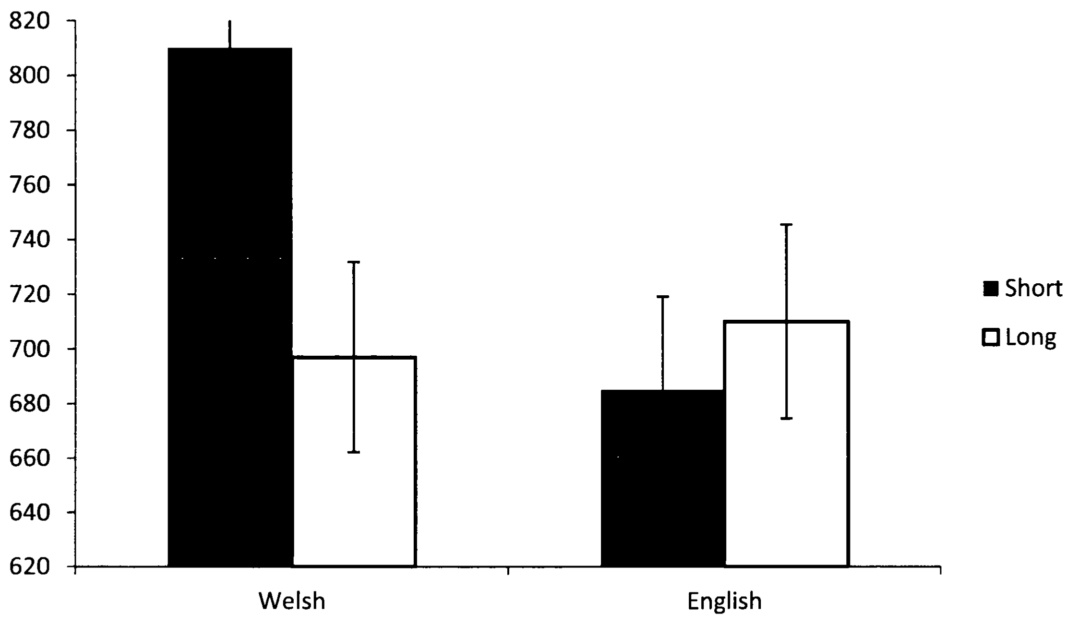


Figure 7.5 Graph of interaction between non-word length and language, showing an effect of length for Welsh but not for English.

7.7.7 Discussion

The aim of the present experiment was to explore the effect of orthographic depth on the length by visual field interaction typically observed in lateralised lexical tasks. Monolingual English speakers and English/Welsh bilinguals performed lateralised lexical decision to English words of different lengths presented in their left and right visual fields. Bilinguals also performed lexical decision on a set of Welsh words. According to the orthographic depth hypothesis, it was predicted that both groups of participants would demonstrate a length by visual field interaction for the orthographically opaque words (i.e., English) but not for the orthographically transparent words (i.e., Welsh).

In line with the predictions, the analysis comparing English performance by monolinguals and bilingual speakers showed a length by visual field interaction that did not vary as a consequence of linguality. Although bilinguals were significantly slower in their responses, the overall pattern of responding in English did not vary between monolinguals and bilinguals. Thus, both groups exhibited a length by visual field interaction, with an effect of length in the LVF but not in the RVF. This is consistent with the results of Beaton, Suller, and Workman (2007), who found similar results in the laterality indices in response to English words from monolingual English speakers and Welsh/English bilingual speakers. Taken together, these results suggest that whilst bilinguals' responses to English words are significantly slower than those of monolinguals (possibly reflecting the fact they have more items in their mental lexicons), the presence of a second language does not affect the length by visual field interaction in English.

Whilst making slower responses than monolinguals, bilinguals were significantly more accurate than monolinguals at identifying both English words and non-words. Thus, whilst bilinguals may be slower to make lexical decisions due to the increased size of their internal lexicons they were also more accurate. This may represent a speed-accuracy trade off, in which an initial search of the lexicon for the target word is more time-consuming but, ultimately, more accurate than that of monolinguals (who, presumably, have far fewer items from which to select a match).

As predicted, reaction times to non-words demonstrated a clear effect of length that did not vary by visual field or linguality. This suggests that both monolinguals and bilinguals were equally affected by visual field and the length of orthographically legal English non-words.

The comparison of bilinguals on each of their languages showed that the length by visual field interaction varied as a function of orthographic depth. As outlined above, for English, bilinguals demonstrated a pattern of responding that was similar, although slower, to that of monolinguals, in that they showed an effect of length in the LVF but not in the RVF. By contrast, in Welsh, bilinguals exhibited an effect of length in both visual fields. This suggests that RVF/LH processing was most disrupted by the presence of Welsh, an orthographically shallow language. Indeed, when recognising Welsh words, the size of the length effect was highly similar in both visual fields (LVF: 51ms; RVF: 48ms).

In general, the results of the present experiment support those of Ktori and Pitchford (2006) and Ziegler, Perry, Jacobs, and Braun (2001) in suggesting that orthographically shallow languages are more prone to length effects than orthographically opaque languages. Furthermore, the results of the current study suggest that under conditions of hemispheric independence, the LH is most affected by orthographic depth, particularly when orthographic depth does not best match the preferred processing style of a given hemisphere. One explanation for how orthographic depth can impact upon hemispheric word recognition concerns the types of processing thought to be conducted in each of the hemispheres. In the RH, processing of visually-presented words is thought to proceed in a sequential manner (e.g. Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988), no matter if the word is familiar or novel. All word and word-like stimuli are processed the same way; hence an effect of length is apparent for both words and non-words alike. The LH is also able to make use of this sequential type of processing for unfamiliar words and non-words (which elicit RVF/LH length effects). However, for familiar words, the LH is able to make use of an efficient lexical look-up procedure which efficiently recognises words on the basis of large and/or whole-word units. This hemispheric asymmetry reflects to some extent the kind of processing thought to be employed when recognising words from shallow and deep orthographies. It has been argued that shallow orthographies, such as Welsh, might rely more on smaller, sub-word chunks for optimal word recognition (e.g. Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992; Ziegler & Goswami, 2005). By contrast, for deeper orthographies - such as English – reliance on very small sub-word chunks frequently leads to inconsistent pronunciations. As such, the most efficient strategy for successful recognition is to use larger sub-word or whole-word chunks. Thus, as the left hemisphere is skilled at reading large sub-word or whole-word units, and as English is most successfully read in that manner, English words may be recognised relatively independently of length. By contrast, Welsh words, which are most efficiently recognised using a small-unit strategy (i.e. a strategy that is not congruous with the preferred processing style of the LH) generate effects of length and are processed in the same way as English and Welsh words presented to the RH.

7.8 General Discussion

Experiments 6 and 7 manipulated word length and orthographic depth in Hebrew speakers (Experiment 6) and English/Welsh bilinguals (Experiment 7). The results from Experiment 6 demonstrated that neither cerebral dominance nor reading direction fully account for visual field asymmetries. Experiment 6 explored the influence of orthographic depth on the reading of two forms of Hebrew script in each of the hemispheres and found that both were equally influenced by the regularity with which the written form of a script represents its phonological forms. Thus, Experiment 6 provided only limited support for the idea that the hemispheres differ in terms of the strategies used to identify laterally-presented words. To explore this idea further, Experiment 7 employed bilingual speakers of English and Welsh, two languages that differ in orthographic depth but not reading direction. The results showed that monolingual and bilinguals demonstrated the same interaction of length and visual field for the recognition of English words. When comparing bilinguals in each of their languages, English words demonstrated a length by visual field interaction whilst Welsh words generated length effects in both visual fields. Thus, Experiment 7 offered some support for the idea that orthographic depth differentially affects each of the hemispheres.

Furthermore, the results of Experiment 7 suggest that bilinguals are able to flexibly adapt to the orthographic depth of the language they are currently reading and employ the most parsimonious strategy for the decoding of written words in each of their languages. As a consequence, it could be argued that the length by visual field advantage will be present for orthographically deep languages but not orthographically shallow languages. However, there is another possible explanation for the present results. Although all participants rated themselves as being fluent in Welsh, they also reported that English was their dominant language. Therefore, it may be the case that the length by visual field advantage, rather than being affected by orthographic depth, is a function of language dominance.

Relative to fluent-reading adults, six year old children have shown large word length effects which diminish with increasing age (Aghababian & Nazir, 2000). Thus, it would seem that the length effect diminishes as a reader becomes increasingly familiar with the printed form of a word in a given language. Furthermore, it has been suggested that the changes experienced by child readers between 6 and 18 (i.e. such as the diminishing length effect) are a consequence of skill rather than simple maturation (Shaywitz, Shaywitz, Pugh, Mencl, Fulbright, Skudlarski, Constable, Marchione, Fletcher, Lyon, & Gore, 2002). If the presence (or absence) of a word length effect is affected by familiarity with the printed form of a given language, then this may have consequences for non-dominant bilinguals in their less fluent language, as they may not be as familiar with the written form of their second language as they are with their first language. As such, in Experiment 7, the different patterns of visual field effects observed for Welsh and for English may have been a function of participants' language dominance; that is, they showed a length by visual field interaction for English (their dominant language, orthographically deep) and length effects in both visual fields for Welsh (their non-dominant language, orthographically shallow). Therefore, to determine if orthographic depth or language dominance causes the pattern of results presented here, the responses of a group of bilinguals who show the opposite pattern of language dominance - that is, an orthographically shallow dominant language and an orthographically deep second language - was examined in Experiments 8 and 9.

Chapter 8: The influence of language dominance on the interaction of length and visual field

The results of the previous experiment suggested that the interaction of length and visual field may be modulated by the orthographic depth of a language. However, it was noted that the results of Experiment 7 could also be explained in another way – that is in terms of language dominance. The bilingual participants of Experiment 7 were fluent in both English and Welsh; however, all participants rated English as their dominant language and Welsh as their non-dominant language. As length effects for children when reading centrally-presented words are known to diminish with increasing reading experience (Aghababian & Nazir, 2000), and as it has been suggested that familiarity with a given script constitutes a form of perceptual training that may lead to facilitation of responses to targets in that script (e.g. Nazir, 2000), it may be the case that the participants in Experiment 7 did not show the interaction of length and visual field when recognising Welsh words due to the fact that they were relatively less experienced in reading written Welsh than they were at reading printed English words. As such, this chapter will briefly outline theoretical accounts of bilinguality and language dominance and will consider how language experience may influence the presence (or absence) of length effects.

8.1 Bilingualism

In its simplest definition, bilingualism can be defined as the ability to speak in two languages (Harley, 2008, p. 153). However, in practice, such a definition is not especially useful as it raises several questions. For example, how well can bilinguals speak each of their languages? Did they learn both languages simultaneously? Can they speak two languages but only use one on a regular basis? Can they also read and write in each of their languages? The answers to these questions shed light on what it means to be bilingual; furthermore, they suggest that bilingualism is a multifaceted concept that is hard to represent along a single continuum that runs from monolingual to bilingual. Whilst an exhaustive review of bilingualism is beyond the scope of this thesis, the present section aims to outline the key concepts that are relevant in understanding the nature of bilingualism and those factors that influence the degree of bilinguality a speaker presents.

8.2 Dimensions of bilinguality

Bilingualism is the norm in some parts of the world. For example, in North Wales, 66% residents are fluent in both Welsh and English (Welsh Language Use Survey, 2004). Even outside notable bilingual areas, many people have communication skills in more than one language. Again using Wales as an example, 12% of the population as a whole rate themselves as fluent speakers; however, a similar number consider themselves able to speak Welsh but not fluently (Welsh Language Use Survey, 2004). Across the population of the world, it is likely that bilingual/multilingual people vastly outnumber monolinguals (Tucker, 1999). Thus, the way in which bilingualism is defined must take into account the wide range of language skills, experience and situations which bilinguals manifest.

A common convention in bilingual research is to refer to the language a bilingual learns first as L1 and their second language as L2. Clearly, this definition applies when learning (or mastery) of one language has begun (or is complete) before the second. Of course, there are many bilinguals who have grown up speaking two languages from birth; in these instances, it is difficult to apply the L1/L2 distinction. However, in practice, even when a speaker has acquired both languages simultaneous, they may still use or favour one of their languages over the other (Baker, 2011, p. 3). Bialystok and Hakuta (1994) have proposed three types of bilinguals, based on when L1 and L2 were acquired: 1) simultaneous bilinguals, who acquire their L1 and L2 at the same time; 2) early sequential bilinguals, who learn L1 first but also learn L2 relatively early in childhood and 3) late bilinguals, who do not begin to start learning L2 until during adolescence or adulthood.

Baker (2011, p. 3) has proposed that bilinguals can be categorised across a range of dimensions. Most notably, bilinguals can differ in terms of their language abilities, with a distinction being drawn between productive capabilities (i.e. speaking and writing) and receptive capabilities (understanding and reading). The ability of bilinguals to use their languages in different ways may be highly dependent on the contexts in which they use their L1 and L2 – for example, in the home, with friends, in work situations etc. Different contexts may cause different patterns of usage to develop, given that some settings (e.g. in the home) may require an emphasis on speaking and listening skills, whereas others (e.g. at work) may rely more on reading and writing skills. Furthermore, the extent to which bilinguals use each of their languages may depend upon their current level of linguistic development. For example, ascendant bilinguals have a strongly-developed L1 and an L2 that is the process of being fully acquired. In contrast, recessive bilinguals are those in whom either L1 or L2 capability is decreasing (possibly due to lack of use or practice).

The theoretical implications of bilinguality on the recognition of visually-presented words will now be considered.

8.3 Models of bilingual word recognition and production

Two models of bilingual word recognition are now briefly reviewed: the Bilingual Interactive Activation model (BIA; Van Heuven, Dijkstra, & Grainger, 1998; BIA+; Van Heuven & Dijkstra, 2002) and the Inhibitory Control model (Green, 1998).

8.3.1 The bilingual interactive activation model (BIA)

The BIA model, in its original (Van Heuven et al, 1998) and updated forms (BIA+; Van Heuven & Dijkstra, 2002) is a model of bilingual word recognition. In its original instantiation, the model proposed an integrated lexicon for L1 and L2, based on the fact that the frequencies of orthographic neighbours from the non-target language were shown to influence recognition latencies for words of the target language. An alternative explanation was subsequently made (Dijkstra, Grainger, & Van Heuven, 1999), in which it was suggested that homographs (words with identical orthographic forms across languages), cognates (words with identical orthographic forms and meaning across languages) and homophones (words with identical phonology across languages) may share the same representations, with the remaining lexical entries stored in separate L1 and L2 lexicons. The model is depicted in Figure 8.1.

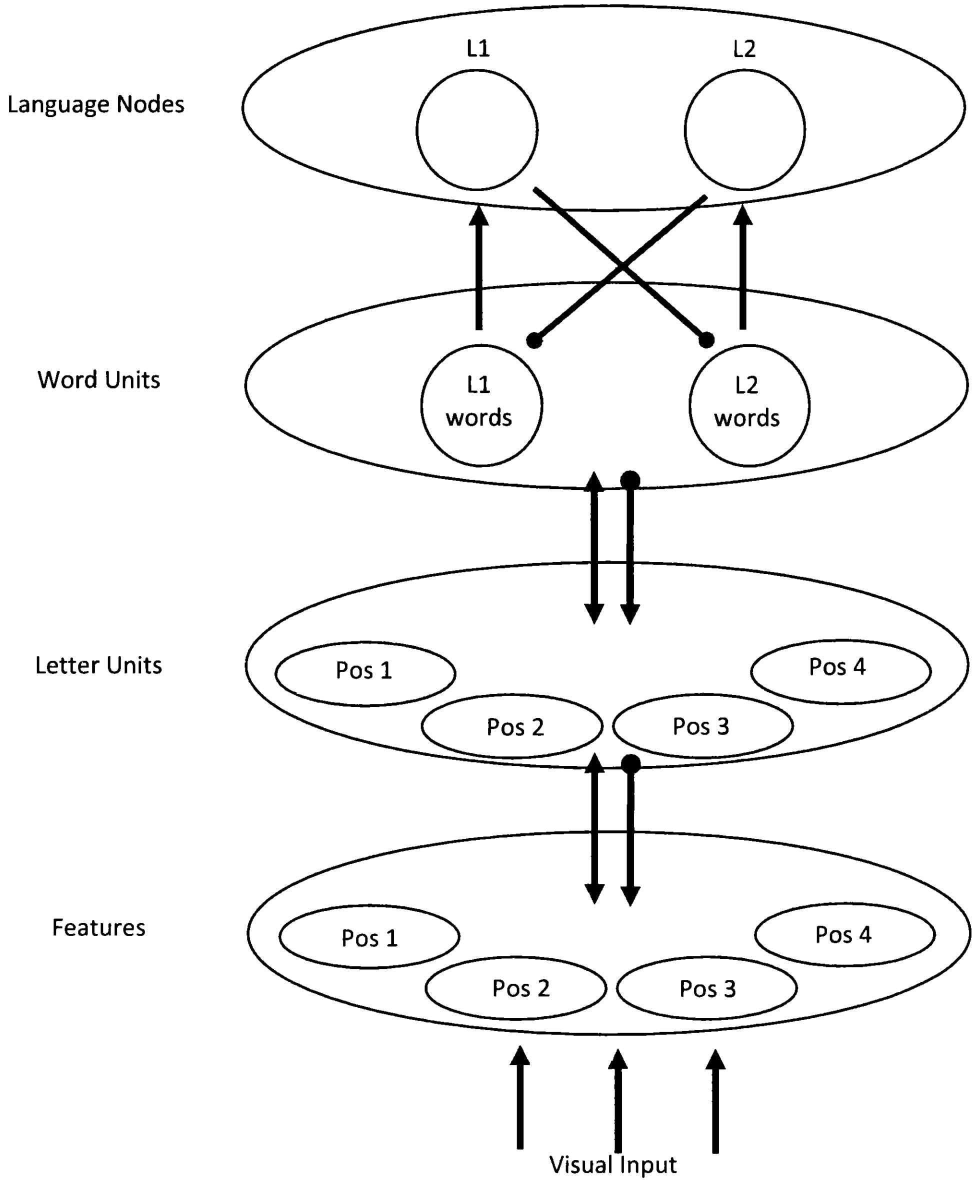


Figure 8.1 Bilingual Interactive Activation Model (BIA; Van Heuven, Dijkstra, & Grainger, 1998)

The BIA model proposes that word recognition in bilinguals is non-language selective in terms of word access. As such, an input letter string causes parallel activation of all words (in both L1 and L2) that share letters with the input string. Words that become active then compete for selection until one surpasses the activation threshold and is recognised. Activation thresholds for each word are thought to depend on their written frequency. A layer of language word units controls the relative activity of L1 and L2 by sending top-down inhibition to the non-target language words. Thus, the BIA model proposes that the early processes involved in the recognition of words by bilinguals in each of their languages is insensitive to whether a target is an L1 word or an L2 word. Words from both languages may become active as a result of bottom-up activation, with a top-down inhibitory mechanism suppressing activity in the non-target language.

8.3.2 The inhibitory control model (IC)

The inhibitory control model (Green, 1998) is a theoretical model of the manner in which bilinguals can use one language without interference from the other. The model is depicted in Figure 8.2.

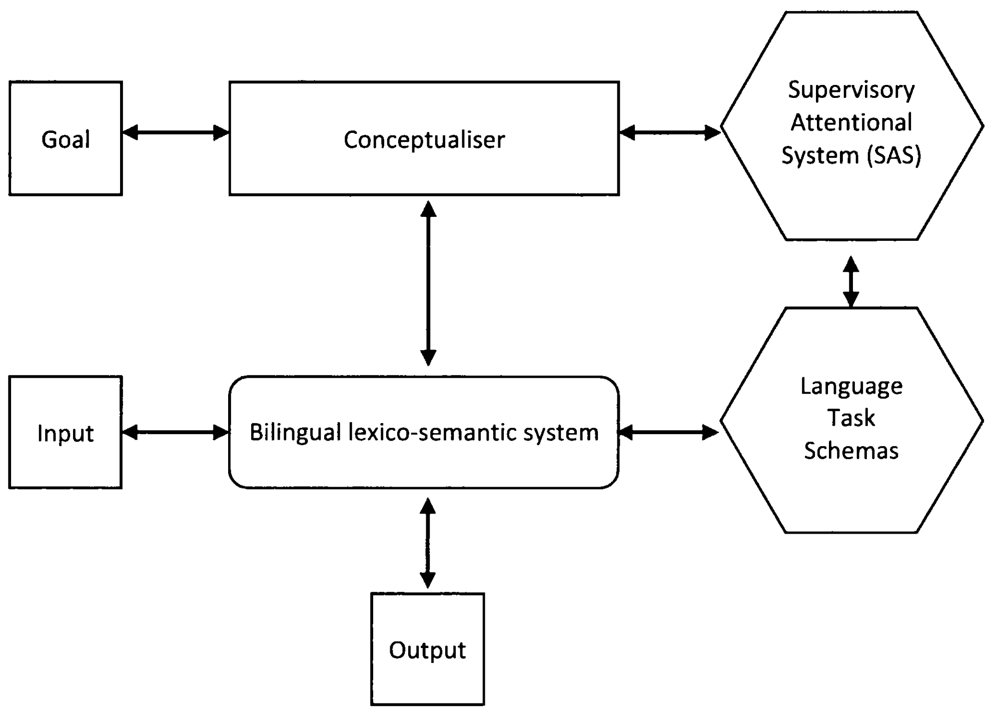


Figure 8.2 The inhibitory control (IC) model (Green, 1998).

The model is organised such that every concept in the lexico-semantic system is linked to a lemma (an abstract representation of a word that contains syntactic and semantic information but no phonological information). Selection of a lemma leads to the activation of the associated word form - known as a lexeme – that contains the necessary phonological information.

In the IC model, the bilingual lexico-semantic system of the bilingual is subject to multiple levels of control. The model proposes that for any linguistic task to be performed, a task schema must first be engaged – for example, naming a picture in

L1 or L2, translating from L1 to L2 etc. The model also proposes a language task mechanism, the purpose of which is to regulate lexical output. It is assumed that an input letter string will activate associated lemmas, irrespective of language. The language task system, governed in turn by an attentional system, is responsible for maintaining the activation of the target language lemmas while inhibiting the lemmas of the non-target language. This inhibitory mechanism provides a possible explanation for the ability of bilinguals to selectively speak in one of their languages without interference from the other.

Both of the models of bilingual word recognition that have been reviewed in the present chapter propose the use of inhibition as a mechanism for suppressing the effects of interference from the non-target language when recognising words in the target language. The way in which experience with a written script may modify the way words are perceived will now be considered.

8.4 The Perceptual Training Hypothesis

Based on the pioneering work of Hebb (1949), Mishkin and Forgays (1952) proposed that reading direction should modify the way a reader perceives print. In particular, Mishkin and Forgays (1952) suggested that, during the course of learning to read, not all areas of the retina become equally trained with written stimuli. Instead, portions of the retina that fall in the direction of reading should be subject to larger effects of perceptual training with printed words than portions of the retina that fall in the direction opposite to that in which the script is read. As reviewed in Chapter 7, Mishkin and Forgays (1952) found support for this proposal by contrasting the recognition of laterally-presented words in two scripts - English and Yiddish - that varied in reading direction. For English, they found an advantage for targets in the RVF; for Yiddish, a script read right-left, they observed a left visual field advantage. On this basis, Mishkin and Forgays (1952) concluded that reading habits fundamentally modify the way a reader perceives written words.

Nazir and colleagues (Nazir, 2000; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004) have argued strongly in favour of a perceptual training account as a means of explaining the length by visual field advantage typically observed for English words in lateralised lexical tasks. On the basis of the optimal viewing position effect (OVP; see Chapter 7 for a review), it is well-established that, for a range of reasons, during natural reading, readers tend to fixate a point within a word that falls somewhere between the beginning and centre of the word. For readers of left-right scripts, one consequence of this OVP effect is that the largest variation in a word's length falls to the right of fixation. Therefore, assuming that perceptual training of the retina occurs in line with Mishkin and Forgays (1952) suggestion, it is possible that portions of the retina that represent the area to the right of fixation may, across time and with extensive practice, develop a form of perceptual expertise with written words that means that fluctuations of word length are handled better in the RVF than in the LVF (Nazir, 2000). Such perceptual learning could become established for areas of the retina that fall in the direction of reading, but would not be easily generalisable to other retinal locations. This is because low-level perceptual learning has been shown to be highly location invariant. For example, when participants learn to identify an unfamiliar visual pattern at one retinal location, subsequent recognition of that pattern is significantly better at the trained location than at any other retinal location (Nazir & O'Regan, 1990). This suggests that this type of perceptual learning effect is highly location- and stimulus- specific and, once established in the RVF, is highly unlikely to generalise to portions of the retina representing the LVF.

Under such a perceptual training account, the lack of RVF length effect in skilled readers of left-right scripts would not be an inherent property of LH processing. Rather, it would be a form of perceptual expertise that develops as reading experience increases. This is in accordance with developmental studies of reading, that have found that length effects diminish between the ages of 6 and 10, presumably as a consequence of the perceptual training involved in learning to read (Aghababian & Nazir, 2000).

Considering bilinguals, if experience with the written form of a script modulates the way printed words are perceived, and if, as outlined above, the development of perceptual training leads to a lack of length effect in the RVF for left-right scripts, it may be the case that bilinguals who are less experienced in reading their L2 may demonstrate a length effect in their RVF due to a lack of perpetual training in processing their L2 script, as compared to their L1 script.

In Experiment 7, it was proposed that the difference in visual field asymmetries observed between fluent readers of English (orthographically opaque) and Welsh (orthographically transparent) may be in explained in terms of the different orthographic depths of each of their languages. However, it was also noted that, whilst classifying themselves as 'fluent' speakers, all participants in Experiment 7 rated English as their dominant language. Thus, it was suggested that one possibility was that the difference in performance of bilinguals on each of their languages may be attributable to language dominance. In that experiment, the pattern of language dominance was such that L1 was an orthographically opaque language and L2 was orthographically transparent. The results of Experiments 6 and 7 provided only partial support for the influence of orthographic depth on the length by visual field interaction. Thus, to further explore the impact of this factor on lateralised word recognition, it would be useful to employ a group of bilinguals who demonstrate the opposite pattern of language dominance – that is, an orthographically transparent L1 and an orthographically opaque L2. Spanish/English bilinguals comprise such a group.

Experiment 8 employs a group of Spanish/English bilingual speakers who performed lateralised lexical decision on short and long words in each of their languages. It was predicted that if orthographic depth influences the interaction of length and visual field, Spanish/English bilinguals should demonstrate an interaction of length and visual field for English but not Spanish. Furthermore, if the length by visual field interaction is modulated by language dominance, it was predicted bilinguals would show an interaction of length and visual field for Spanish but not English.

8.5 Experiment 8

8.5.1 Method

8.5.1.1 Participants

Twenty three Spanish/English bilinguals who had Spanish as their native language (7 male, 16 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 18-27 (mean age: 21). All were rated as strongly right-handed (>80%) by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £30 in return for their participation. Participants were given a short questionnaire about their language skills. On average, bilingual participants had been learning their second language (Spanish) since 11 years of age and, on a scale of 1-7 (1 being very low and 7 being as a native speaker), bilinguals rated their reading and listening skills in English as 5 and their writing and speaking skills in English as 5.

8.5.1.2 Materials

Two lists of stimuli were developed – a set of English items and a set of Spanish items. The English items experiment comprised 200 words and 200 orthographically legal non-words. Non-words were generated from the ARC Non-word database (Rastle, Harrington, & Coltheart, 2002). A set of 400 Spanish words and non-words was also drawn up. Words were matched in terms of length, *N,* and frequency across languages. For each language, half of the stimuli were four letters in length and half were eight letters in length. Words were matched for frequency across sets (from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993)) and number of orthographic neighbours (*N*) within each word length. The negative correlation observed between word length and N (i.e. the shorter the word, the higher the number of orthographic neighbours) rendered the match for *N* across word lengths impracticable. For this reason *N* was matched within but not across lengths. Four letter words had a mean *N* size of 9.84 and eight letter words had on average 0.57 orthographic neighbours.

Item lexicality (word/non-word), language (English/Spanish), visual field (left/right) and string length (short/long) were orthogonally manipulated, leading to sixteen experimental conditions: (1) English four-letter words LVF; (2) English four-letter words RVF; (3) English eight-letter words LVF; (4) English eight-letter words RVF; (5) English four-letter non-words LVF; (6) English four-letter non-words RVF; (7) English eight-letter non-words LVF; (8) English eight-letter non-words RVF; (9) Spanish four-letter words LVF; (10) Spanish four-letter words RVF; (11) Spanish eight-letter words LVF; (12) Spanish eight-letter words RVF; (13) Spanish four-letter non-words LVF; (14) Spanish four-letter non-words RVF; (15) Spanish eight-letter non-words LVF and (16) Spanish eight-letter non-words RVF. All items were presented once only. Each condition consisted of fifty items.

8.5.1.3 Apparatus and procedure

The experiment was organised into two blocks – English and Spanish. Half of the participants performed the English block first then the Spanish. This order was reversed for the remaining participants. Each block began with 40 practice trials (20 words and 20 non-words) different from those used as experimental stimuli but maintaining the same string lengths (4-letters and 8-letters items). The experimental stimuli were presented once the practice was over. Participants were instructed to decide if the item on the screen was a real or an invented word. Participants were exposed to a total of 800 experimental trials. Stimuli presentation was randomised and controlled by an IBM Pentium computer, with a 586 processor and 17 inches SVGA display. Participants sat at a viewing distance of 57cm from the display screen in a comfortable chair with a headrest. The experiment was programmed and implemented using E-Prime software (Psychology Software Tools, 2007).

All stimuli were presented in lower-case, Arial font, size 14. To minimise flicker, words appeared white against a blue background and were presented in the centre of the screen. The central fixation cross subtended a visual angle of 1°.

Each language block was further sub-divided into ten randomised blocks of 40 items. This was to allow participants to take regular rest breaks. Item selection for each block was randomised and controlled by the experimental program. At the end of each 40-item block, participants could take a break and trials recommenced once the participant pressed one of the keys on the response box. Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 150m, to the left or to the right of fixation. Stimuli were laterally displaced such that the last letter of LVF and the first letter of RVF stimuli were 2° from fixation.

The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, a message appeared on the screen for 2000ms, indicating that their response had been recorded. Immediately after that, the next fixation-cross reappeared as the next trial began. The importance of fixating on the cross during the task was emphasised in the experimental instructions, as was the need for speed and accuracy. Participants were also instructed not to blink during trials. During the practice trials, participants were trained in how to time their blinks such that they occurred after experimental trials.

8.5.1.4 ERP Acquisition and Processing

The electroencephalogram (EEG) was recorded in an electrically-shielded EEG chamber housed within the Department of Psychology, Swansea University, UK. Participants sat in a comfortable seat, at a viewing distance of 57cm from the screen, and were instructed to refrain from moving, blinking or making eye movements during experimental trials. Data were recorded from 64 Ag/AgCl electrodes (BioSemi Active II System, BioSemi Systems, Amsterdam, NL) mounted on an electrode cap and arranged according to the extended International 10-20 system. Sampling rate was 500Hz and a 0.1-30Hz bandpass filter was applied. Data were converted off-line to the average reference and analysed using BESA Research 5.3 (BESA GmbH, 2011). Upon completion of the experimental testing session, participants performed an eye movement calibration task for use in eye artefact rejection (Berg & Scherg, 1994).

8.5.1.5 EEG Pre-Processing

The continuous EEG for each participant was divided into epochs of 1000ms in length, beginning 200ms pre-stimulus onset. Trials contaminated with eye artifacts or with peak-to-peak potential differences larger than 75μv in any channel were rejected. All epochs were baseline-corrected over the 200ms pre-stimulus interval and converted to the average reference.

8.5.2 Behavioural Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (5% of all trials). This led to two participants being excluded from subsequent analyses due to excessive levels of anticipatory responses. Error responses (12%) were rejected from subsequent analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 8.1.

Only correct responses were analysed. A repeated-measures ANOVA was conducted on RT data by subjects (F_1), with word length (short vs. long), language (English vs. Spanish) and visual field (LVF vs. RVF) as within-subjects factors. A by-items analysis was also conducted (F_2), with word length, language and visual field as between-subjects factors.

Table 8.1. Mean reaction times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of visual field (LVF vs. RVF), word length (short 4-letter vs. long 8-letter), language (English vs. Spanish) and target lexicality (word vs. non-word) in Experiment 8.

			ENGLISH WORDS			
	Left Visual Field (LVF)			Right Visual Field (RVF)		
	Short	Long	Difference	Short	Long	Difference
M	497	583	86	490	548	58
SD	67	88		81	85	
% Acc	95	85		93	91	
			ENGLISH NONWORDS			
M	698	694	-4	663	665	2
SD	137	152		126	149	
% Acc	80	75		79	78	
			SPANISH WORDS			
	Left Visual Field (LVF)			Right Visual Field (RVF)		
	Short	Long	Difference	Short	Long	Difference
M	587	610	23	567	585	18
SD	127	134		149	128	
% Acc	84	88		87	92	
			SPANISH NONWORDS			
M	654	844	190	653	786	133
SD	132	240		145	210	
% Acc	91	76		92	83	

8.5.2.1 Responses to words

8.5.2.1.1 Reaction Time

Participants responded to English words (530ms) faster than to Spanish words (587ms): $F_1(1,20) = 5.62$, MSe = 119850.04, $p < .05$, $\eta^2_p = .25$; $F_2(1,792) = 50.53$, MSe = 228040.46, $p < .001$, $\eta^2_p = .60$. A main effect of length indicated that RTs to short words (536ms) were significantly faster than those to long words (582ms): $F_1(1,20) = 30.53$, MSe = 76141.23, $p < .001$, $\eta^2_p = .64$; $F_2(1,792) = 46.93$, MSe = 636029.82, $p < .001$, $\eta^2_p = .56$. Similarly, words presented in the RVF (548ms) were identified faster than those presented in the LVF (569ms): $F_1(1,20) = 10.69$, MSe = 17101.95, $p < .005$, $\eta^2_p = .39$; $F_2(1,792) = 8.62$, MSe = 116787.97, $p < .005$, $\eta^2_p = .11$. Finally, Language and length interacted by-items and by-subjects: $F_1(1,20) = 18.16$, MSe = 23365.76, $p < .001$, $\eta^2_p = .52$; $F_2(1,792) = 10.22$, MSe = 138580.04, $p < .001$, $\eta^2_p = .13$. This interaction is depicted in Figure 8.3. The three-way interaction of language, length and visual field was not significant: $F_1(1,20) = 8.82$, MSe = 1095.22, $p = .85$, $\eta^2_p = .05$; $F_2(1,792) = 1.05$, MSe = 9.75, $p = .97$, $\eta^2_p = .03$.

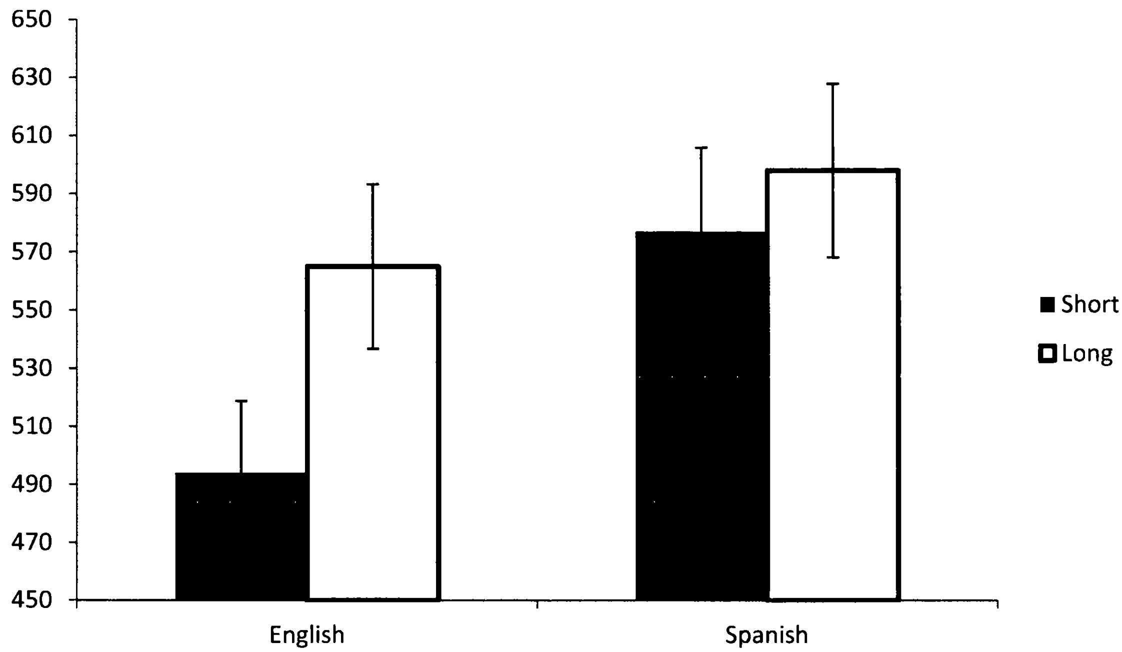


Figure 8.3: Graph of interaction between word length and language. *y*-axis is measured in milliseconds.

Post-hoc comparisons indicated that the effect of length was larger in English (71ms; $p = .001$) than in Spanish (21ms; $p = .03$). Furthermore, short English words (494ms) were identified significantly faster than short Spanish words (577ms; $p < .01$). Long English and long Spanish words were recognised with equivalent latencies ($p > .1$).

8.5.2.1.2 Accuracy

Responses to words were more accurate for English items (91%) than Spanish (88%): $F_1(1,20) = 8.31$, MSe = 413.44, $p < .01$, $\eta^2_p = .33$; $F_2(1,792) = 4.51$, MSe = 963.12, $p < .01$, $\eta^2_p = .06$.

Language and length interacted by-subjects but not by-items: $F_1(1,20) = 36.61$, MSe = 1111.11, $p < .001$, $\eta^2_p = .68$. For English words, short words (94%) were more accurately identified than long words (88%). The opposite was true for Spanish, with long words (90%) being recognised more accurately than short words (86%).

By-subjects, length and visual field interacted: $F_2(1,792) = 4.29$, MSe = 914.70, $p < .01$, $\eta^2_p = .39$. Across languages, short words (88%) were identified more accurately than long words (81%; p = .001). In the RVF, short and long words were identified with equivalent levels of accuracy (short: 88%; long: 87%; $p = .14$).

Finally, language, length and visual field interacted by-subjects but not by-items: $F_1(1,20) = 12.86$, MSe = 121.00, $p < .01$, $\eta^2_p = .31$. This interaction is depicted in Figure 8.4. Post-hoc comparisons showed that the nature of this interaction was such that, for English, short words were identified more accurately than long words in the LVF. In the RVF, short and long words were recognised equally accurately. For Spanish, in both visual fields, long words were identified more accurately than short words.

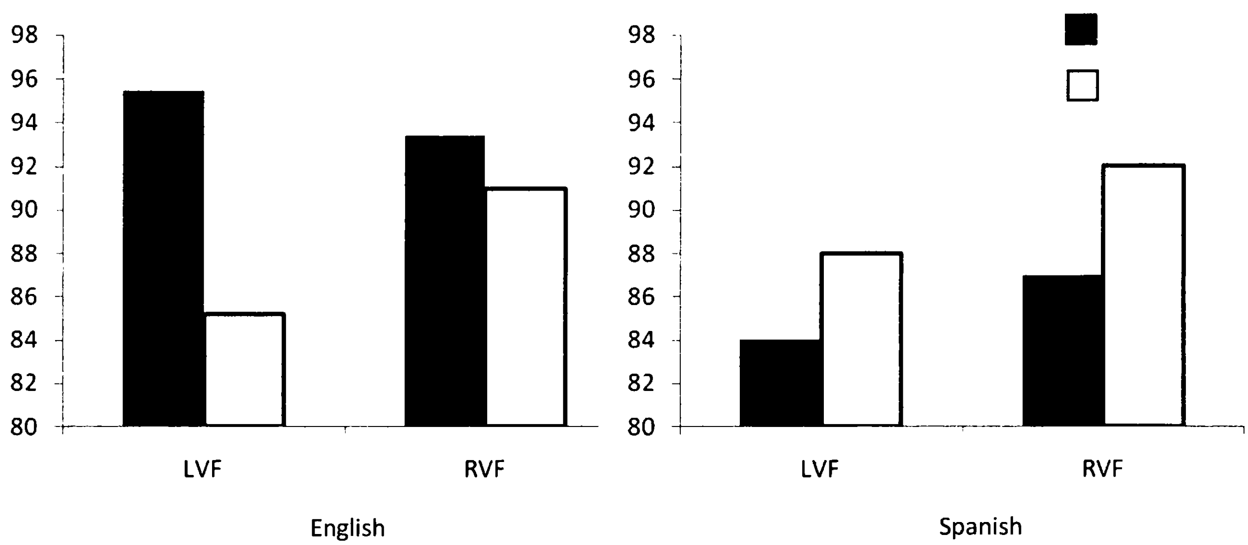


Figure 8.4. Interaction between language, word length and visual field. *y*-axis is response accuracy (%). Note that, for English, short words are recognised more accurately than long words in both visual fields. For Spanish, long words are more accurate than short words.

8.5.2.2 Responses to non-words

8.5.2.2.1 Reaction Time

Two ANOVA analyses - one by-subjects and one by–items - were conducted with language, visual field, and string length as within-subjects factors by-subjects and between-subjects factors by-items. A main effect of length was observed: $F_1(1,20) = 23.87$, MSe = 229863.78, $p < .001$, $\eta^2_p = .58$; $F_2(1,792) = 75.74$, MSe = 563695.02, $p <$

.001, η^2_p = .16. Short non words (667ms) were identified faster than long non words (747ms). Non-words presented to the RVF (691ms) were recognised significantly faster than those presented to the LVF (723ms): $F_1(1,20)$ = 13.66, MSe = 35149.92, p < .005, η^2_p = .47; $F_2(1,792)$ = 10.77, MSe = 80127.97, p < .001, η^2_p = .27.

Language and length interacted, by-items and by-subjects: $F_1(1,20)$ = 37.38, MSe = 236677.37, p < .001, η^2_p = .69; $F_2(1,792)$ = 98.58, MSe = 733612.73, p < .001, η^2_p = .20. Post-hoc comparisons showed that short non-words were identified equally quickly in both languages. By contrast, long non-words were rejected significantly faster in English (679ms) than in Spanish (815ms; p = .001).

Finally, language, length and visual fields interacted by-subjects: $F_1(1,20)$ = 12.52, MSe = 8812.11, p < .01, η^2_p = .42. For English, responses to RVF non-words were faster than those to LVF non-words, regardless of length. This was also true of long Spanish non-words, where were identified faster in the RVF (786ms) than in the LVF (844ms; p = .001). By contrast, short Spanish non-words were recognised with equivalent levels of accuracy in both visual fields (LVF: 654ms, RVF: 653ms; p = .84).

8.5.2.2.2 Accuracy

Participants rejected Spanish non-words (86%) with significantly greater accuracy than English non-words (78%): $F_1(1,20)$ = 12.61, MSe = 2177.78, p < .01, η^2_p = .43; $F_2(1,792)$ = 30.03, MSe = 6049.38, p < .001, η^2_p = .07. Across languages, short non-words (85%) were rejected more accurately than long non-words (78%): $F_1(1,20)$ = 16.61, MSe = 2055.11, p < .001, η^2_p = .49; $F_2(1,792)$ = 28.34, MSe = 5708.64, p < .001, η^2_p = .07. By-subjects, non-words presented to the RVF (83%) were responded to with significantly greater accuracy than those presented to the LVF (80%): $F_1(1,20)$ = 6.27, MSe = 245.44, p < .05, η^2_p = .27.

Language and length interacted, by-items and by-subjects: $F_1(1,20)$ = 15.15, MSe = 841.00, p < .001, η^2_p = .47; $F_2(1,792)$ = 11.60, MSe = 2336.11, p < .001, η^2_p = .29. Post-hoc comparisons indicated that, for Spanish, short non-words (92%) were identified more accurately than long non-words (79%). Short and long English non-words were identified equally well. Short Spanish non-words (92%) were identified significantly more accurately than short English non-words (79%). Accuracy to non-words did not differ as a function of language.

8.5.3 Electrophysiological Results

Only trials with correct responses were included in ERP analyses. Grand average RMS curves (Figure 8.5) plotted for all conditions across time, indicated four main peaks in the ERP distribution, at 100ms, 180ms, 250 and 330ms post-stimulus onset. These peaks were considered for analysis since they occurred before participants' average response time for words (558 ms). For each peak, grand average topographies were examined and time-windows of interest were selected as follows: for the peak at 100ms, the maximal positive deflection between 70 and 130 ms (corresponding to the P1 component); for the peak at 180ms, the maximal negative deflection between 130 and 230ms (corresponding to the N170); for the peak at 250ms, the maximal positive deflection between 180ms and 280ms and for the peak at 330ms, the maximal negative deflection between 280 and 380ms over occipitotemporal sites. Analyses were focused on two groups of electrodes, formed from the average of PO3, PO7 and P7 over the left hemisphere and PO4, PO8 and P8 over the right hemisphere.

8.5.3.1 Preliminary Analyses

To assess how successfully the current paradigm stimulated the intended hemisphere, prior to the main analyses, activity evoked by both contralateral and ipsilateral presentation was examined for P1 and N1 components. Table 8.2 presents mean amplitudes and peak latencies for P1 and N1 components for contra- and ipsilateral presentation collapsed across length and language. Previous lateralised ERP studies have found that both P1 and N1 components peak earlier for contralaterally-presented than for ipsilaterally-presented stimuli (e.g., Doyle & Rugg, 1998) and that N1 amplitudes are larger for contralaterally-presented items than ipsilaterally-presented items (Coulson, Federmeier, Van Petten, & Kutas, 2005; Doyle & Rugg, 1998; Hillyard & Anllo-Vento, 1998). Thus, in the present analyses, an interaction between visual field and hemisphere was expected to serve as an index of how successfully stimuli were directed to the contralateral hemisphere.

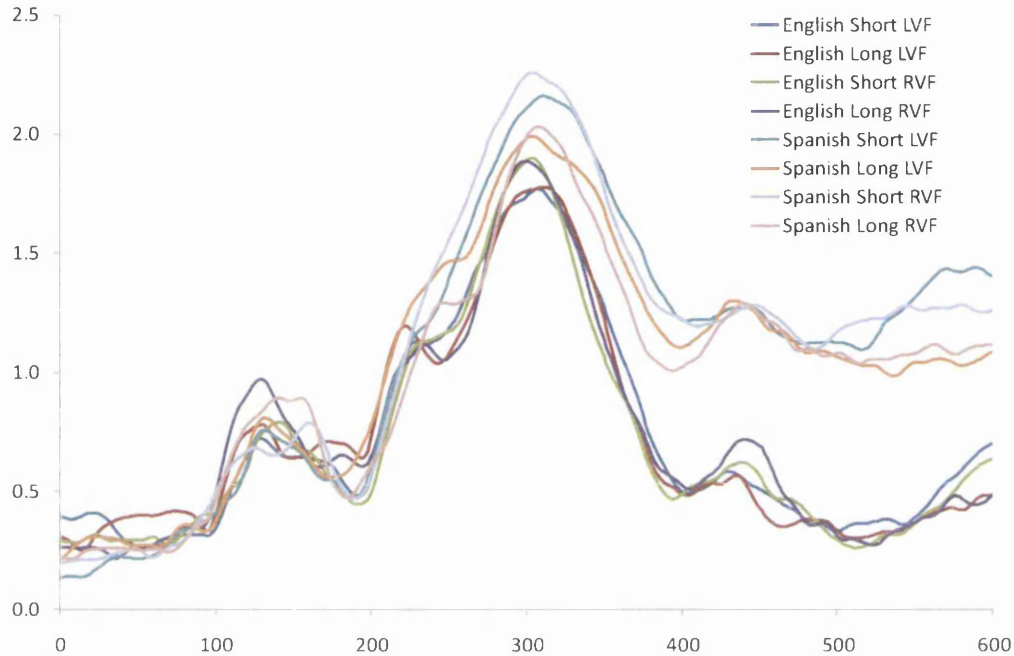


Figure 8.5. Grand average RMS curves plotted for all conditions across all electrodes. *x*-axis is in milliseconds; *y*-axis is in microvolts (μv).

Table 8.2: Mean Amplitude and Peak Latencies for P1 and N1 components evoked by contra- and ipsilaterally-presented words, collapsed across word length and language for Experiment 8

	Left Hemisphere		Right Hemisphere	
	LVF	RVF	LVF	RVF
Amplitude				
P1	.39	.34	.43	.68
N1	1.05	-1.17	-.70	1.36
Latency				
P1	120	95	98	121
N1	164	156	155	166

Four repeated measures ANOVAs were conducted separately on latency and amplitude for the P1 and N1 components, with visual field and hemisphere as within-subjects factors in each analysis.

For the P1 component, a visual field by hemisphere interaction showed that amplitudes to contralaterally-presented stimuli peaked earlier than those to ipsilaterally-presented items: $F(1,17) = 45.73$, MSe = 42534.72, $p < .001$, $\eta^2_p = .73$. There were no independent main effects of either visual field or hemisphere. Mean amplitudes did not vary by visual field, hemisphere or an interaction of both factors at 100ms.

The interaction of visual field and hemisphere was evident in both mean amplitude and peak latency measures on the N1 component. In terms of latency, contralaterally-presented words achieved peak latency before ipsilaterally-presented items in both hemispheres: $F(1,17) = 5.81$, MSe = 6658.25, $p < .05$, $\eta^2_p = .26$. The interaction was also present for mean amplitudes: $F(1,17) = 39.54$, MSe = 329.80, $p < .001$, $\eta^2_p = .70$, with amplitudes to contralaterally-presented items being larger than those to ipsilaterally-presented items in both hemispheres.

These preliminary analyses indicate the paradigm was successful in stimulating the intended hemisphere. As such, all subsequent analyses focus on contralaterally-presented items only. Mean amplitudes and peak latency were analysed using two repeated-measures ANOVAs, with language (English vs. Spanish), recording site (LH vs. RH) and string length (short vs. long) as within-subjects factors.

In the present experiment only language, visual field and letter length were considered as the variables of interest. Due to the difficulty in interpreting higher-order interactions with ANOVA, lexicality was not included as a factor in the ERP analyses.

8.5.3.2 Event Related Potentials (ERPs)

8.5.3.2.1 Responses to words

Figure 8.6 presents topographic scalp maps of the rear of the head for all word conditions plotted across all time windows. Figure 8.7 presents ERP curves for all contralateral word conditions plotted over the left and right hemispheres.

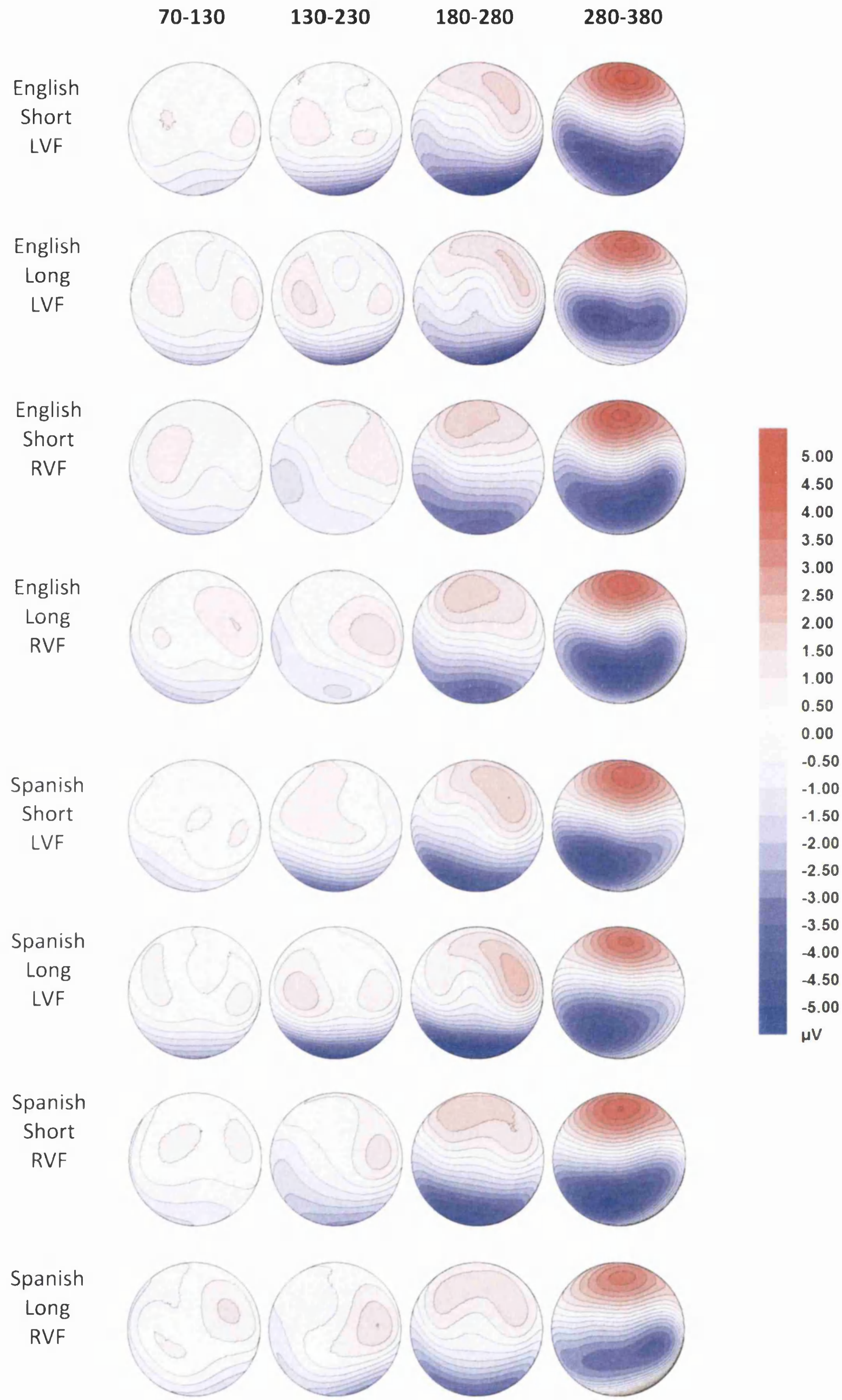


Figure 8.6 Topographic scalp maps of the rear of the head plotted for all word conditions across all time windows.

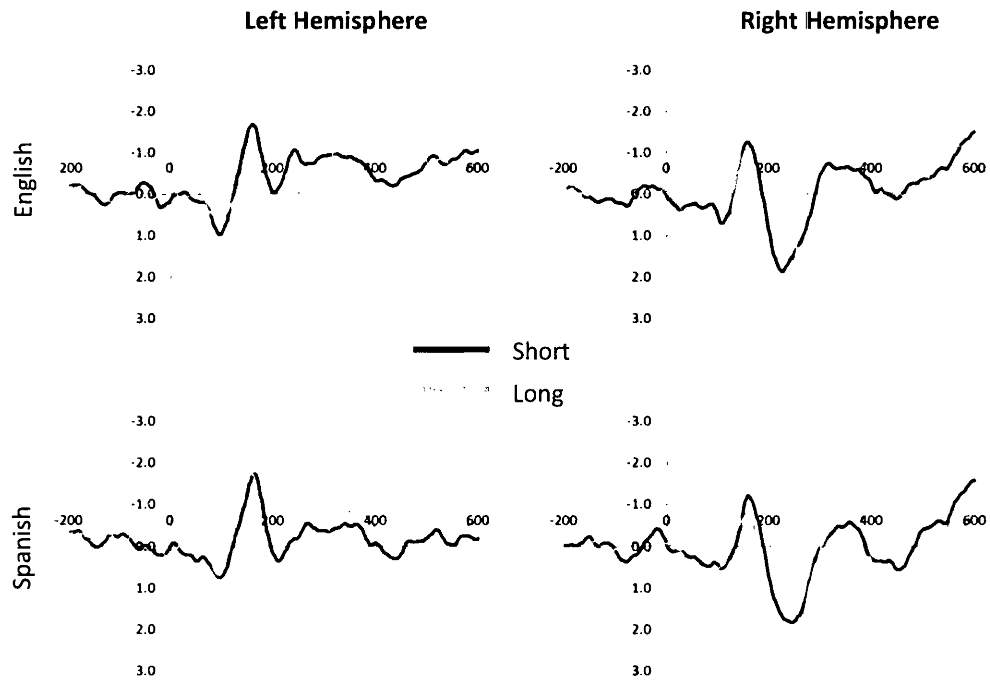


Figure 8.7 ERP curves for contralaterally-presented words plotted over the left and right hemispheres for English and Spanish. *x*-axis is in milliseconds; *y*-axis is in microvolts.

8.5.3.2.2 P1 Mean Amplitude and Peak Latency

No significant effects on either amplitude or latency were present at 100ms.

8.5.3.2.3 N1 Mean Amplitude and Peak Latency

A clear hemispheric asymmetry was evident on N1 amplitudes: $F(1,17) = 6.32$, MSe = 28.08, $p < .05$, $\eta^2_p = .27$. Amplitudes recorded over the LH (-.49μv) were significantly more negative than those recorded over the RH (.40μv). Similarly, short words (-.29μv) evoked significantly larger negativities than long words (.20μv). There was no main effect of language: $F(1,17) = 1.55$, MSe = 19.52, $p = .09$, $\eta^2_p = .02$, no interaction of language and length [$F(1,17) = 6.44$, MSe = 254.25, $p = .19$, η^2_p = .078], language and hemisphere [$F(1,17) = 5.58$, MSe = 111.11, $p = .10$, $\eta^2_p = .16$] or length and hemisphere [$F(1,17) = 9.67$, MSe = 467.88, p = ..08, $\eta^2_p = .36$] and no three-way interaction of length, language and hemisphere [$F(1,17) = 1.01$, MSe = 11.17, $p = .77$, $\eta^2_p = .02$].

Analysis of peak latency demonstrated that amplitudes recorded over the RH (160ms) peaked significantly earlier than in the LH (175ms).

8.5.3.2.4 P2 Mean Amplitude and Peak Latency

Voltages recorded over the RH (1.41μv) were larger than those recorded over the LH (-.07μv) between 180-280ms: $F(1,17) = 12.16$, MSe = 78.50, $p < .005$, $\eta^2_p = .42$. Similarly, long words (.95μv) generated significantly larger voltages than short words (.38μv): $F(1,17) = 21.50$, MSe = 11.78, $p < .001$, $\eta^2_p = .56$. There was no main effect of language: $F(1,17) = 12.05$, MSe = 1.06, $p = .77$, $\eta^2_p = .09$, no interaction of language and length [$F(1,17) = 5.19$, MSe = 316.25, $p = .22$, $\eta^2_p = .01$], language and hemisphere [$F(1,17) = 1.89$, MSe = 121.45, $p = .50$, $\eta^2_p = .20$] or length and hemisphere [$F(1,17) = 4.24$, MSe = 97.95, $p = .10$, $\eta^2_p = .40$] and no three-way interaction of length, language and hemisphere [$F(1,17) = 16.54$, MSe = 156.44, $p = .9$, $\eta^2_p = .11$].

No latency effects were present between 180-280ms.

8.5.3.2.5 N2 Mean Amplitude and Peak Latency

Amplitudes between 280-380ms were significantly larger for long words (.95μv) than for short words (-.51μv): $F(1,17) = 10.13$, MSe = 7.00, $p < .01$, $\eta^2_p = .37$. There was no main effect of either hemisphere $F(1,17) = 10.13$, MSe = 7.00, $p < .01$, $\eta^2_p = .37$ or language $F(1,17) = 10.13$, MSe = 7.00, $p < .01$, $\eta^2_p = .37$ and no interaction of language and length [$F(1,17) = 14.02$, MSe = 115.77, $p = .12$, $\eta^2_p = .12$], language and hemisphere [$F(1,17) = 0.97$, MSe = 11.15, $p = .80$, $\eta^2_p = .01$] or length and hemisphere [$F(1,17) = 2.58$, MSe = 14.58, $p = .84$, $\eta^2_p = .02$] and no three-way interaction of length, language and hemisphere [$F(1,17) = 3.38$, MSe = 77.95, $p = .65$, $\eta^2_p = .05$].

Analysis of peak latency demonstrated a main effect of language between 280-380ms: $F(1,17) = 12.16$, MSe = 78.50, $p < .01$, $\eta^2_p = .42$. English words (327ms) reached peak latency significantly earlier than Spanish words (336ms).

8.5.4 Discussion

The present experiment sought to examine whether the effects of orthographic depth found in Experiment 7 could be explained by the fact that the regular language was also the non-dominant language. In the present experiment, dominant Spanish-English bilingual speakers were asked to recognise laterally-presented words and non-words of different lengths in both languages. It was predicted that, if the length by visual field interaction is modulated by orthographic depth (as in Experiment 7), a length by visual field interaction should be present for English but not Spanish. If the length by visual field interaction is modulated by language dominance, it should be present in Spanish but not English.

The influence of orthographic depth in the hemispheric processing of short and long words was partially demonstrated in the present experiment. This is because a length by visual field interaction was evident for English but not Spanish in terms of response accuracy. Thus, for English, response accuracy was a function of length in the LVF but not in the RVF. For Spanish, a length effect was present in both visual fields. Response times showed a main effect of length and no interactions. Table 8.1 shows that response time trends are in accordance with the orthographic depth hypothesis. The effect of length was larger for the English words presented in the LVF (86 ms) than for the English words presented in the RVF (58 ms). The difference in the size of the length effect for the recognition of Spanish words was much smaller in both visual fields (LVF = 23 ms; RVF = 18 ms).

An unexpected effect of language was found, with responses to L2 English words being significantly faster and more accurate that those to L1 Spanish words. There may be several reasons for this. One potential explanation is that as bilinguals are assumed to be unable to switch off one of their languages in order to perform in the other (e.g. Kroll, Bobb, & Wodniecka, 2006), the lack of dominance in English (participants rated their level of English as 5 on a scale of 1 to 6 (1 being very low fluency, 7 being native speaker ability; range 4-6) and the difficulty of the task instigated a strong inhibition of the first language in order to avoid interferences from the dominant language and to maximise successful completion of the task. The inhibition of the dominant language might also explain the reason why long words were identified more accurately than short words. This might have been because the inhibition might not be of evenly applied to all the words in the language but, instead, may be stronger for the 'easier' words (i.e., short words) than for the more difficult words such as long words.

In the ERP analysis, the earliest effects of language were not evident until 280-380ms, relatively late in the processing cycle. This supports the BIA model (Van Heuven et al., 1998), which proposes that early processes in the recognition of printed words in bilinguals are not-language specific. In keeping with this, the ERP analyses in the present chapter demonstrated that early responses (P1, N1 and P2) did not differ as a function of language. Instead, the current data suggest that the neural activity that underpins the early processing of short and long words in a bilingual's two languages may be highly similar and that language-specific processes may not become important until later in the processing cycle.

The first effects of length were evident between 130-230ms, at which time short words generated more activity than long words. At both the P2 and N2 components, this pattern of activity had reversed and long words generated larger responses than short words. Thus, as shown in Experiment 2 (Chapter 5) with monolingual speakers, ERPs showed a shifting effect of length that changed across time, with short words producing larger responses early on and long words becoming more active later in the processing stream.

The interaction of language, length and visual field observed in the behavioural data for response accuracy was not reflected in the ERP analysis. In contrast, the interaction of length and visual field for English was represented in the ERP analysis on the N1 component in Experiment 2, although, in that experiment, the interaction was present behaviourally in terms of reaction time. In the present experiment, the interaction between length, language and visual field was manifest in the accuracy analysis.

On the N2 component, amplitudes to English words peaked earlier than those to Spanish words. This may reflect the fact that the behavioural results of the present experiment demonstrated an unexpected pattern, such that bilinguals were faster and more accurate to respond in their L2 than in their L1. This facilitation for L2 over L1 may have arisen due to a strategy of strongly inhibiting L1 in order to perform well in L2. It might also be the case that this effect for better responses to L2 words than L1 words may have been exacerbated by the lateralised presentation. That is, the strategy of inhibiting L1 in order to perform well in L2 could be depending on task difficulty, the more difficult the task the largest inhibition of L1. In order to test whether the inherent difficulty of the lateralised presentation of stimuli caused the language effect observed in Experiment 8, the same stimuli were used in a lexical decision task where words were centrally-presented. A different group of dominant Spanish-English bilinguals with similar language experiences as those individuals that participated in Experiment 8 took part in Experiment 9.

8.6 Experiment 9

The purpose of Experiment 9 was to further explore the effect of word length in each of the hemispheres of bilingual speakers of Spanish and English. Experiment 8 provided some support for the idea that the interaction of length and visual field is influenced by orthographic depth. To further explore this, while making the task easier to perform, Experiment 9 manipulated orthographic depth for centrally-presented words of different lengths. It was predicted that if orthographic depth affects word length effect, Spanish/English bilinguals would show a larger effect of length in Spanish than in English. Conversely, if length effects are influenced by language dominance, it was predicted that bilinguals would show larger length effects in their non-dominant language than in their dominant language. Additionally, due to an unexpected language effect in Experiment 8, where bilinguals demonstrated faster and more accurate behavioural responses to L2 than L1 words, Experiment 9 sought to determine whether the unexpected language effect observed in Experiment 8 was an artefact of lateral presentation. As such, if the language effect observed in Experiment 8 was a function of the difficulty of the task, it was predicted that it would disappear or be reduced under 'easier' conditions such as central presentation. If the language effect is a genuine effect and not an artefact of lateralised presentation, it should persist under central presentation.

Furthermore, as reported in Chapter 3, language-specific hemispheric asymmetries on the N170 component for centrally-presented words have been reported. For German native-speakers, words, non-words and consonant strings alike have been shown to evoke N170s of equivalent sizes in the LH (Maurer, Brem, Bucher, & Brandeis, 2005). In English, however, words are strongly left-lateralised on the N170, whereas non-words are not (Maurer, Brandeis, & McCandliss, 2005). Given that English and German vary in respect of orthographic depth - with German being highly regular and transparent and English being less regular and more opaque - Maurer and McCandliss (2008) suggest that the different lateralisation patterns of words and non-words in the two languages may reflect the extent to which grapheme-phoneme conversion is employed. As German is highly regular, grapheme-phoneme conversion may be the default mode of reading employed by German speakers, whether they read words or non-words; thus, the finding that words and non-words alike generate equivalent N170s. By contrast, due to the fact that English is less regular than German, English readers may rely less on grapheme-phoneme conversion for legal words and more for non-words. This results in a pattern of N170 activity that is left lateralised for words but not for non-words. If this is the case, the N170 may be a marker of the mapping of graphemes to phonemes. Thus, given that Spanish (like German) is more transparent in its grapheme-phoneme conversion rules than English, if orthographic depth differentially affects hemispheric asymmetries in the processing of centrally-presented words, this will be reflected on the N170 component. Specifically, it is predicted that if orthographic depth affects the processing of words at 170ms, N170 responses will be left-lateralised for Spanish words and non-words. It will also show a left-wards asymmetry for English words but not non-words.

8.6.1 Method

8.6.1.1 Participants

Thirteen Spanish/English bilinguals who had Spanish as their native language (6 male, 7 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 18-25 (mean age: 20). All were rated as strongly right-handed (>80%) by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £15 in return for their participation. Participants were given a short questionnaire about their language skills. On average, bilingual participants had been learning their second language (Spanish) since 10 years of age and, on a scale of 1-7 (1 being very low and 7 being as a native speaker), bilinguals rated their reading and listening skills in Spanish as 5 and their writing and speaking skills in Spanish as 5.

8.6.1.2 Materials

The English items used in this experiment comprised the same 400 words and orthographically legal non-words used in Experiment 8. The Spanish items were also the same 400 words and non words as those used in Experiment 8. Words were matched in terms of length, *N,* and frequency across languages. For each language, half of the stimuli were four letters in length and half were eight letters in length. Item lexicality (word/non-word), language (English/Spanish) and string length (short/long) were orthogonally manipulated, leading to eight experimental conditions: (1) English four-letter words; (2) English eight-letter words; (3) English four-letter non-words (4) English eight-letter non-words; (5) Spanish four-letter words; (6) Spanish eight-letter words; (7) Spanish four-letter non-words and (8) Spanish eight-letter non-words. All items were presented once only. Each condition consisted of 100 stimuli.

8.6.1.3 Apparatus and procedure

The procedure employed was the same as used in Experiment 8, except words were presented centrally rather than laterally.

8.6.1.4 ERP Acquisition and Processing

Acquisition of the EEG signal was the same as in Experiment 8.

8.6.1.5 EEG Pre-Processing

As in Experiment 8

8.6.2 Results

8.6.2.1 Behavioural Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from further analyses (2.32% of all trials). This led to two participants being excluded from subsequent analyses due to excessive levels of anticipatory responses. Error responses (12.9%) were rejected from subsequent analyses. Mean reaction times, standard deviations and accuracy rates are presented in Table 8.3.

Only correct responses were analysed. A repeated-measures ANOVA was conducted on RT data with word length (short vs. long) and language (English vs. Spanish) as within-subjects factors in a by-subjects analysis and with word length and language as a between-subjects factors in a by-items analysis.

Table 8.3 Mean reaction times (M), standard deviations (SD) and percentage accuracy (% Acc) as a function of word length, language and target lexicality in Experiment 9

	WORDS			
	English		Spanish	
	4 Letter	8 Letter	4 Letter	8 Letter
M	369	389	426	393
SD	138	156	125	134
% Acc	92	92	86	96
	NON-WORDS			
M	538	563	511	559
SD	227	299	182	190
%Acc	79	72	94	91

8.6.2.2 Responses to words

8.6.2.2.1 Reaction Time

No main effects of length or language were present in the RT data. However, these factors interacted by-subjects and by-items: $F_1(1,10) = 17.19$, MSe = 7498.75, $p < .01$, $\eta^2_p = .63$; $F_2(1,796) = 19.68$, MSe = 113593.16, $p < .001$, $\eta^2_p = .47$. For English words, short words (369ms) were recognised significantly faster than long words (389ms). This pattern was reversed for Spanish words, with short words (426ms) being identified reliably slower than long words (393ms). Long words were recognised equally quickly in both languages (English: 389ms, Spanish: 393ms; $p = .84$). However, participants recognised English short words (369ms) faster than Spanish short words (426ms; $p = .001$).

8.6.2.2.2 Accuracy

Long words were identified more accurately than short words, by-subjects and by-items: $F_1(1,10) = 24.09$, MSe = 295.36, $p < .001$, $\eta^2_p = .71$; $F_2(1,796) = 18.28$, MSe = 1685.12, $p < .05$, $\eta^2_p = .44$.

Length and language interacted by-subjects and by-items: $F_1(1,10) = 31.86$, MSe = 327.27, $p < .001$, $\eta^2_p = .76$; $F_2(1,796) = 20.05$, MSe = 2975.21, $p < .001$, $\eta^2_p = .49$. Post-hoc pairwise comparisons indicated that short and long English words were recognised equally well (both 92% accuracy). For Spanish words, long words (96%) were recognised significantly more accurately than short words (92%; $p = .001$).

8.6.2.3 Responses to non-words

8.6.2.3.1 Reaction Time

Short non-words (525ms) were recognised faster than long non-words (561ms) by-items and by-subjects: $F_1(1,10) = 6.57$, MSe = 14426.97, $p < .05$, $\eta^2_p = .40$; $F_2(1,796) = 26.70$, MSe = 422363.19, $p < .001$, $\eta^2_p = .63$. By-items, a main effect of language demonstrated that Spanish non-words (534ms) were recognised faster than English non-words (564ms): $F_2(1,796) = 9.47$, MSe = 85993.08, $p < .05$, $\eta^2_p = .23$.

8.6.2.3.2 Accuracy

A main effect of language indicated that participants recognised Spanish non-words (92%) more accurately than English non-words (76%), by-subjects and by-items: $F_1(1,10) = 43.32$, MSe = 3061.11, $p < .001$, $\eta^2_p = .81$; $F_2(1,796) = 123.30$, MSe = 27828.31, $p < .001$, $\eta^2_p = .24$. A main effect of non-word length was also present, with short non-words (87%) being recognised more accurately than long non-words (81%): $F_1(1,10) = 9.16$, MSe = 311.11, $p < .05$, $\eta^2_p = .47$; $F_2(1,796) = 12.53$, MSe = 2828.31, $p < .001$, $\eta^2_p = .31$.

8.6.2.3.3 Electrophysiological Results

Only trials with correct responses were included in ERP analyses. Grand average RMS curves (Figure 8.8), plotted for all conditions across all electrodes, indicated three prominent peaks in the ERP distribution, at 100ms, 180ms and 300ms post-stimulus onset. These peaks were considered for analysis since they occurred before the participant's average response time (397ms). For each peak, grand average topographies were examined and time-windows of interest were selected as follows: for the peak at 100ms, the maximal positive deflection between 75 and 125 ms (corresponding to the P1 component); for the peak at 180ms, the maximal negative deflection between 130 and 230ms (corresponding to the N170) and for the peak at 300ms, the maximal positive deflection between 250ms and 350ms over occipitotemporal sites. The focus of interest was on electrodes PO3, PO7 and P7 over the left hemisphere and on PO4, PO8 and P8 over the right hemisphere. These sites were selected for analysis on the basis of their reported sensitivity to the orthographic properties of words (Bentin et al, 1999). As the focus of the present study was on hemispheric differences, to maximise the hemispheric comparison, the three electrodes over each hemisphere were analysed as a single group.

ERPs were analysed for mean voltage computed across time windows that spanned the peaks of the components of interest. Peak latencies were also computed and analysed. Thus, three-way repeated-measures ANOVAs were conducted separately on mean voltage and peak latency for the peaks at 100ms, 180ms and 300ms, with hemisphere (left vs. right), language (Spanish vs. English), lexicality (word vs. non-word) and word length (short vs. long) as within-subjects factors. Lexicality was not included in the ERP analysis of the previous experiment, in order to reduce the number of factors involved in the statistical analyses and avoid the problems inherent in analysing higher-order interactions. However, in the present experiment, as visual field was not a factor, lexicality was reintroduced as a factor in the ERP analyses. All pairwise comparisons are reported using the Bonferroni correction to control for multiple comparisons (all $p < .05$ unless otherwise stated).

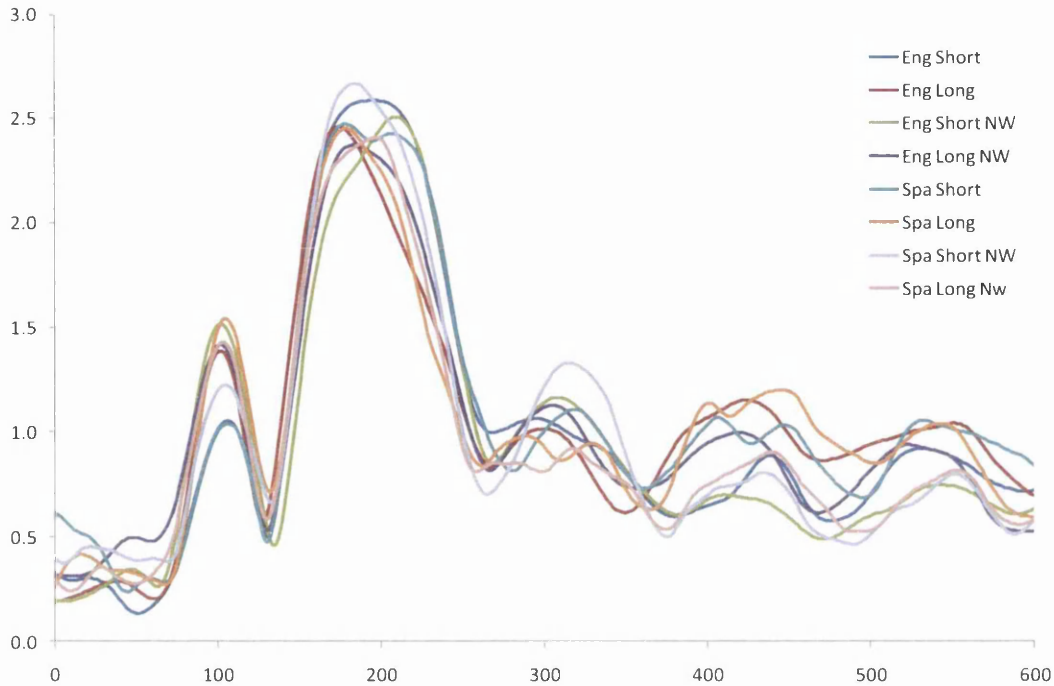


Figure 8.8 Grand average RMS curves for all conditions plotted across all electrodes.

8.6.2.4 Event Related Potentials (ERPs)

8.6.2.4.1 Responses to words

Figure 8.9 presents topographic scalp maps of the rear of the head for all conditions plotted across all time windows. Figure 8.10 presents grand average ERP curves for all conditions plotted over the left and right hemispheres.

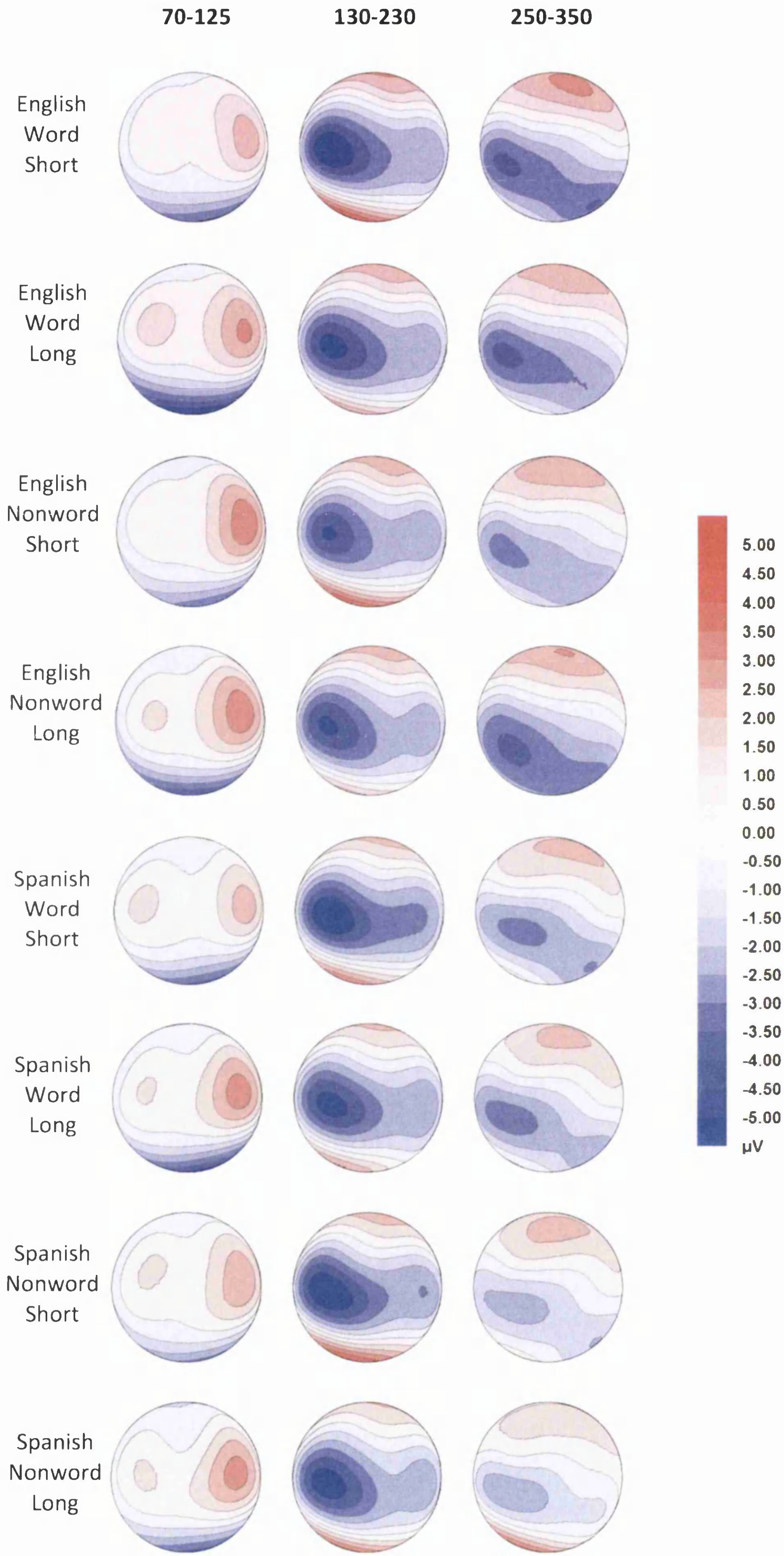


Figure 8.9 Topographic scalp maps of the rear of the head plotted for all conditions

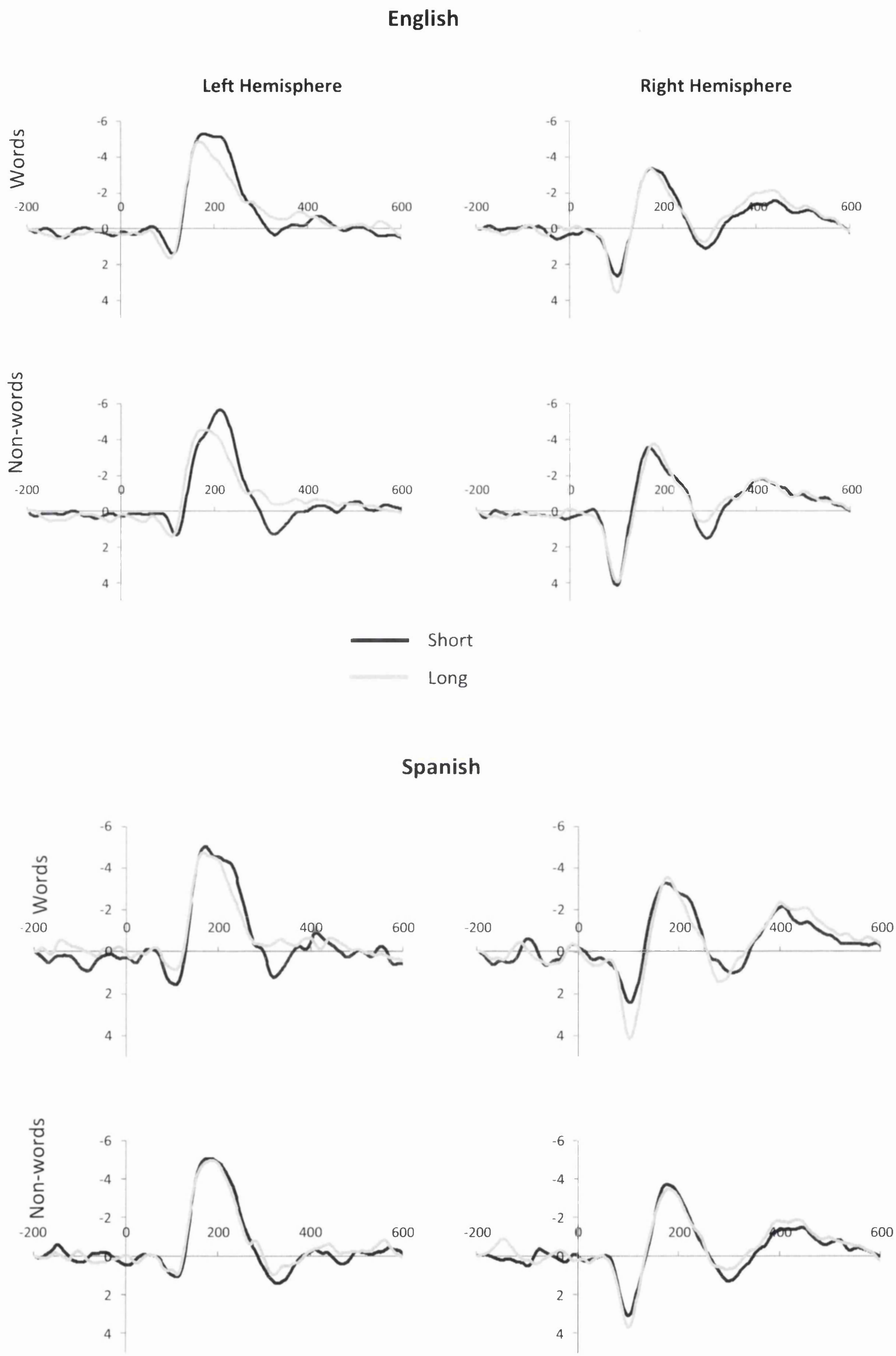


Figure 8.10 ERP curves for English (top panels) and Spanish (bottom panels), plotted for all conditions over the left and right hemisphere. *x*-axis is in milliseconds; *y*-axis is measured in microvolts.

8.6.2.4.2 P1 Mean Amplitude and Peak Latency

At 100ms, amplitudes to English words (1.77μv) were larger than those evoked by Spanish words (1.60μv): $F(1,10) = 5.538$, MSe = 1.23, $p < .05$, $\eta^2_p = .36$. Similarly, amplitudes recorded over the RH (2.63μv) were significantly more positive than those recorded over LH sites (.74μv): $F(1,10) = 12.28$, MSe = 157.77, $p < .01$, $\eta^2_p = .55$.

Across languages, lexicality exerted a differential effect on each of the hemispheres: $F(1,10) = 5.538$, MSe = 1.23, $p < .05$, $\eta^2_p = .36$. In the LH, voltages evoked by words and non-words were statistically similar (LH: .81μv; RH: .68μv; $p = .47$). In the RH, amplitudes to non-words (2.84μv) were significantly higher than those of words (2.43μv; $p = .009$).

Language, length and hemisphere interacted at 100ms: $F(1,10) = 9.58$, MSe = 2.44, $p < .01$, $\eta^2_p = .49$. For Spanish words, amplitudes did not vary as a function of length in either the left or right hemispheres. For English, in the LH amplitudes to long words (.97μv) were significantly more positive than those to short words (.63μv; $p = .04$). In the RH, amplitudes to short and long English words did not differ.

No latency effects were evident at 100ms.

8.6.2.4.3 N170 Mean Amplitude and Peak Latency

A clear hemispheric asymmetry was evident at 170ms: $F(1,10) = 5.99$, MSe = 178.68, $p < .05$, $\eta^2_p = .38$. Voltages recorded over the LH (-4.27μv) were significantly more negative than those over the RH (-2.56μv).

Hemisphere, language and lexicality interacted at 170ms: $F(1,10) = 5.13$, MSe = .92 , $p < .05$, $\eta^2_p = .34$. The nature of this interaction was such that, for Spanish words, amplitudes over the LH were significantly more negative than those over the RH for both words (p=.05) and non-words alike ($p = .03$). This was also true for English words (p=.03). Amplitudes to English non-words, however, were statistically similar across hemispheres.

Analysis of peak latency demonstrated a main effect of string length, with long items (192ms) achieving peak voltage significantly earlier than short items (186ms): $F(1,10) = 5.59$, MSe = 2176.78 , $p < .05$, $\eta^2_p = .37$. Lastly, language and lexicality interacted: $F(1,10) = 10.23$, MSe = 648.69 , $p < .01$, $\eta^2_p = .51$. For English items, words (188ms) peaked earlier than non-words (193ms). For Spanish items, words (188ms) and non-words (186ms) achieved peak amplitude at statistically similar latencies.

8.6.2.4.4 ~300 Mean Amplitude and Peak Latency

At 300ms, responses to Spanish words (-.68μv) were more positive than those to English words (-1.25μv): $F(1,10) = 7.10$, MSe = 14.57 , $p < .05$, $\eta^2_p = .42$. A main effect of length was also present: $F(1,10) = 9.97$, MSe = 4.17 , $p < .01$, $\eta^2_p = .50$, with amplitudes to short words (-.81μv) being more positive than those to long words (-1.12μv). Similarly, voltages recorded over the RH (-.05μv) were significantly larger than those over the LH (-1.88μv): $F(1,10) = 6.32$, MSe = 147.74 , $p < .05$, $\eta^2_p = .39$.

String length and lexicality interacted: $F(1,10) = 12.43$, MSe = 2.04 , $p < .005$, $\eta^2_p = .53$. Short and long words evoked similar voltages (short: -1.02μv ; long: -1.29μv; $p = .27$). For non-words, short items (-.60μv) generated more positive voltages than long non-words (-1.1μv).

Analysis of peak latency revealed a main effect of length, with long words (295ms) achieving peak amplitude earlier than short words (309ms): $F(1,10) = 46.28$, MSe = 7673.29 , $p < .001$, $\eta^2_p = .82$. Similarly, amplitudes recorded over the RH (288ms) peaked significantly before the LH (316ms): $F(1,10) = 27.22$, MSe = 32737.93 , $p < .001$, $\eta^2_p = .73$.

Length and hemisphere interacted at ~300ms: $F(1,10) = 6.56$, MSe = 2374.67 , $p < .05$, $\eta^2_p = .39$. In the RH, short and long items peaked at similar latencies ($p = .09$). In the LH, long items (305ms) achieved peak amplitude significantly earlier than short items (326ms).

Finally, a three-way interaction of language, length and lexicality was evident at ~300ms: $F(1,10) = 5.05$, MSe = 824.17 , $p < .05$, $\eta^2_p = .37$. For English items, short and long words were recognised with equivalent latencies (p = .23); for non-words, long non-words (293ms) reached their peak amplitude significantly earlier than short non-words (313nms). This pattern was reversed for Spanish – long words (292ms) peaked earlier than short words (307ms), whilst short and long non-words peaked at statistically equivalent latencies (p = .11).

8.6.3 Discussion

The present experiment sought to examine the effect of increasing word length on the behavioural and electrophysiological responses of Spanish/English bilinguals whilst recognising centrally-presented words in each of their languages. It was predicted that if the presence of length effects is influenced by orthographic depth, bilinguals should demonstrate larger length effects in Spanish than in English. If length effects are affected by language dominance, it was predicted that a larger length effect would be present in English (L2) than Spanish (L1). An additional prediction was made concerning language effects. Given the unexpected pattern of behavioural responses found in Experiment 8, wherein bilinguals were faster and more accurate in their L2 than their L1, it was predicted that if that language effect was a consequence of the difficulty of lateralised presentation, the effect would not be evident in the present experiment. If the language effect reflected a genuine facilitation for L2 over L1, it would also be present for centrally-presented words.

The absence of a main effect of language indicated that participants' performance was equivalent across each of their languages. This suggests that the facilitation for L2 identified in the previous experiment was an artefact of lateralised presentation. Thus, the task may have been particularly difficult for bilinguals, who may have concentrated their efforts on performing well in L2, to the detriment of their L1.

In the present experiment, the interaction found between language and letter length was surprising. For English, bilingual participants recognised short words faster 20ms faster than long words. By contrast, the opposite pattern was true for Spanish words, with long words being identified 33ms faster. This pattern was also evident in the accuracy analysis. Furthermore, the ERP data at 300ms demonstrated that activity for long Spanish words peaked significantly earlier than for short

Spanish words. Taken together, these behavioural and electrophysiological findings suggest that, in the present experiment, word length differentially affected L1 and L2 in a group of Spanish/English bilinguals. This is particularly surprising as previous research has suggested that, for orthographically transparent languages (such as Spanish), word length effects for centrally-presented words should be larger than for orthographically opaque languages, such as English (Ziegler, Perry, Jacobs, and Braun, 2001), possibly due to differences in the optimal strategy with which words are recognised in each type of language (Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992; Ziegler & Goswami, 2005).

One possible reason for this unexpected finding is the difference in *N* between word sets. In the present experiment, *N* was matched across languages but not across lengths. Thus, for both languages, it was the case that short words had more orthographic neighbours than long words. Previous research has tended to show facilitative effects of large *N* on lexical decision (e.g. Andrews, 1997). However, whilst English and Spanish words were matched in terms of *N*, it may be the case that *N* differentially affects each language. For example, for lexical decision of English words, the effect of *N* has been shown to be facilitatory (e.g. Andrews, 1997). By contrast, manipulation of *N* in Spanish has shown reduced or null effects for central presentation (Carreiras, Perea, & Grainger, 1997) and inhibitory effects for RVF presentation, possibly as a consequence of increased lexical competition in the LH (Perea, Acha, & Fraga, 2007). Thus, it may be the case that the relatively large *N* of short words (compared to long words) in Spanish may have served to inhibit responses to short words such that long words were identified faster and more accurately. In addition, the *N* size of the English short words – which was the same as the Spanish short words - may be less inhibitory for English as L2 than for Spanish as L1. For example, *hair* has five neighbours - *fair, hail, heir, lair, pair* (these neighbours are taken from CELEX). However, if English is your L2, it is possible you may be unfamiliar with *hail, heir, and lair*. Thus, the fact that these words are unknown to you may effectively reduced the number of possible neighbours in the mental lexicon, possibly reducing lexical competition and making recognition of a target faster and more accurate. Thus, it may be the case that *N* size in L2 may not be the same as for L1, due to the fact that L2 is not as fully developed as L1, meaning L2 has fewer items in competition with each other than L1. The effect of *N* on the recognition of targets in bilinguals' L1 and L2 is an avenue of future possible research.

In the ERP analysis, an early effect of language was found. At 100ms, amplitudes to English words were larger than those to Spanish words. This suggests that, in the present experiment, the language of a target word was discriminated early on in the processing cycle. This is in contrast to the results of Experiment 8, where the earliest effects of language emerged at 280ms. This may be attributable to the fact that laterally-presented words may be initially less well-perceived that centrally-presented words. Thus, in the present experiment, processing may have been able to progress to a language-specific phase much faster than for laterally-presented words. However, the early language-specific effect may also be attributable to the fact that bilinguals exhibit different levels of perceptual expertise with English and Spanish words, being more familiar with Spanish words. As such, it may be the case that this early difference between languages may represent the neural correlates of the low-level perceptual learning that is thought to arise from extensive experience with one script as opposed to another, less familiar script.

Evidence for the differential effect of orthographic depth was identified in the ERP analysis on the N1 component. At 170ms, for Spanish, both words and non-words elicited negativity that was larger over the LH than the RH. For English words, this left-wards asymmetry was present for words but not for non-words, which generated amplitudes of equivalent magnitude across both hemispheres. This finding is in keeping with both the results of Experiment 1 – where monolingual English speakers also demonstrated a LH asymmetry for words but not non-words at 170ms – and those of Maurer, Brandeis, and McCandliss (2005). Of particular relevance to the present study, Maurer, Brandeis, and McCandliss (2005) have reported language-specific differences between words and non-words in respect of the N170. For German native-speakers, words, non-words and consonant strings alike have been shown to evoke N170s of equivalent sizes (Maurer, Brem, Bucher, & Brandeis, 2005). In English, however, words are more strongly left-lateralised than non-words, as indexed by the size of the N170 (Maurer, Brandeis, & McCandliss, 2005). Thus, the results of the present study support those of Maurer, Brandeis, and McCandliss (2005) and Maurer, Brem, Bucher, & Brandeis (2005), in demonstrating that the N170 component for words and non-words is differentially affected by the regularity with which graphemes in a given language represent phonemes. For Spanish, which is highly regular and which can be read successfully on the basis of small sub-word chunks, the ERP evidence from the present experiments suggests that both words and non-words are read in a similar manner. For English, LH N170 activity is larger for words than for non-words, supporting the view that words and non-words are recognised in qualitatively different ways.

Thus, the results of the present experiment strongly suggest that the effect of increasing string length differs between English and Spanish, both behaviourally and electrophysiologically. Behaviourally, an interaction of length and language was present, showing a small (but significant) length effect was present for English words and a reverse length effect – where long words were recognised faster and more accurately than short words – for Spanish words. This is contrary to previous research (e.g. Frost, Katz, & Bentin, 1987), which has associated larger length effects with increasing orthographic transparency. Evidence for the influence of orthographic depth on the processing of words was evident in the ERP analysis at 170ms, suggesting that words and non-words are processed in a similar manner in Spanish and in fundamentally different ways in English. Finally, some evidence was found to support the perceptual training hypothesis. At 100ms, amplitudes to English and Spanish items were statistically different, possibly reflecting the early neural correlates of perceptual expertise with a given script.

Chapter 9: The impact of format distorition on the length by visual field interaction

The interaction of word length and visual field in lateralized lexical tasks is a robust finding in the word recognition literature (Ellis, 2004). As previously discussed, the presence or absence of a length effect has often been taken as an indicator of the type of lexical processing that is occurring at any given time. Hence, the classic interaction of length by visual field for laterally-presented words – giving rise to an effect of length in the LVF but not the RVF – has typically been taken as evidence to suggest the LH processes familiar words holistically or in a parallel-like manner, whilst the RH utilizes a length-dependent, more sequential type of processing.

Whilst the effect of word length in each of the cerebral hemispheres is typically explored using horizontally presented words, some studies have used non-standard presentation formats in order to further understanding of how word length affects the recognition of printed words (Bub & Lewine, 1988; Lavidor & Ellis, 2001; Young & Ellis, 1985). For the purposes of the present chapter, two types of non-standard presentation will be considered: vertical presentation (also known as *marquee*, where a word is presented vertically, with each letter underneath the preceding letter) and rotated presentation (where the entire word is rotated *x*° from the horizontal plane). An example of the types of stimulus orientation considered in the present chapter is given in Figure 9.1.

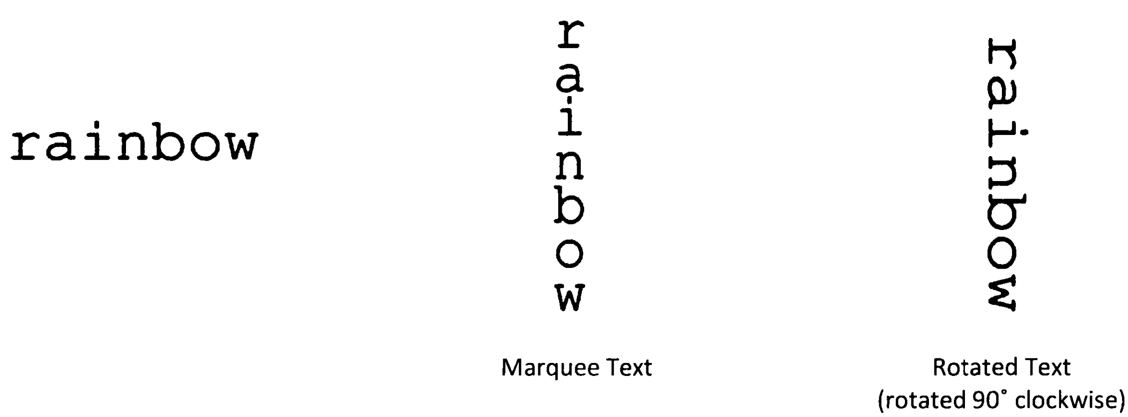


Figure 9.1 Example of horizontal, marquee and rotated text

This chapter reviews the effect of presentation format on word recognition and reading with a particular – although not exclusive - focus on those studies that have also examined word length and visual field differences.

An early report of vertically-presented words in lateralized word recognition is that of, Cohen-Leehey, and Cahn (1979). They presented vertical words (all of 4 letters in length) to the left and right visual fields of participants. Using accuracy as a dependent measure, Cohen, Leehey, and Cahn (1979) found a right visual field advantage for the recognition of words, suggesting that the LH's enhanced ability to recognise words also applies to vertically-presented words.

In a similar vein, studies by Young and Ellis (1985) and Bub and Lewine (1988) found enhanced performance for the RVF using vertically-presented words (Young & Ellis (1985) using a lexical decision task; Bub & Lewine (1988) using a word naming task). In both studies, short and long words were presented to each of the visual fields. The length by visual field interaction was reported in both studies for horizontally presented words. However, critically, the size of the length effect for vertically presented words was equal across visual fields. In Bub and Lewine (1985), the length effect in the RVF was only 13ms per letter for horizontally-presented words but 25ms per letter for vertically-presented words. In the LVF, the size of the length effect was 30ms per letter, irrespective of whether the word was horizontally or vertically-presented. This suggests that when words are printed in a non-standard format, whilst the LH may demonstrate an overall superiority, it nonetheless becomes subject to effects of length that are equivalent to those typically observed in the RH.

Howell and Bryden (1987) presented a combination of horizontal and vertically-presented words to the left and right visual fields. Stimuli were 168 words and 168 non-words, between four and six letters in length. Results from their first experiment demonstrated an interaction of visual field and word orientation indicating a RVF advantage for horizontal words but no hemispheric advantage for vertically-presented words. Similarly, length and orientation interacted, such that response latencies to vertical words were more a function of length than those to horizontal words.

In a second experiment, Howell and Bryden (1987) presented the same stimuli blocked by orientation. Other than an overall speeding of RTs, the pattern of findings was remarkably similar to their first experiment: a RVF superiority in terms of RT for horizontal words but not for vertically-presented strings and an interaction of string length and word orientation, revealing a larger length effect for vertical than horizontal presentation. Strikingly, Howell and Bryden (1987) did not find the commonly reported interaction between length and visual field for horizontally-presented words. This could have been the result of operationalising length in three levels (4-letters, 5-letters and 6-letters) rather than a division into two levels (short and long), which is more frequently used. The differences between each of the three levels might not have been powerful enough to show a length effect and/or an interaction.

Finally, Jordan and Patching (2003) directly compared the effect of horizontal and vertically-presented words and non-words in the left and right visual fields. Word length was matched across conditions. Using a Reicher-Wheeler task in combination with an eye-tracker - to stringently control central fixation - Jordan and Patching (2003) found that responses to RVF words were more accurate than LVF words. For vertical items, there was no RVF advantage for either words or non-words. In addition, the effect of lexicality was only significant in the RVF, where words were identified more accurately than non-words.

One of the few studies to employ the three orientation formats used in the present chapter (i.e., horizontal, marquee and rotated) is that of Byrne (2002). In particular, Byrne (2002) was interested in determining which of the two vertical formats (i.e., marquee or rotated) was processed more efficiently. Results showed that centrally-presented horizontal words were named fastest, followed by words rotated 90° clockwise or counter-clockwise (with no difference between the direction of rotation), followed by marquee words. Although this study used central presentation and involved participants reading entire sheets of stimuli, the results nonetheless reflect a difference in the ease with which words presented in two similar non-standard formats (i.e., vertical) are read.

Koriat and Norman (1985) also employed central presentation to investigate the effect of rotation on the perception of written words. In a series of experiments, Hebrew words ranging from 2-5 letters in length were rotated through 60°, 120° and 180°. In terms of RT, horizontal words and words rotated 60° demonstrated no significant effect of length. By contrast, words rotated either 120° or 180° both showed large effects of length. In a second experiment, 3- and 4-letters words only were used. Words were manipulated such that all words, irrespective of letter length, were the same physical length on the screen. Results showed larger effects of orientation for 4-letter words than for 3-letter words. Thus, this suggests that the effect is not related to the physical size of a stimulus but, rather, is dependent on the number of letters in the string. A final experiment employed a wide range of rotations, in an attempt to ascertain the point at which a length effect becomes established. Words were rotated between 0°-340°, in 20° increments. It was found that length effects were not apparent until 60°, confirming the results of their first experiment. Thus, the results of Koriat and Norman's (1985) research suggests that 60° is a critical angle for word recognition – for rotation of <60°, holistic word recognition processes are still in operation, as evidenced by no significant effect of length at this angle. Above 60°, it would seem that words are recognised in a more sequential, letter-by-letter manner that is more length dependent and, hence, gives rise to larger length effects.

Cohen, Dehaene, Vinckier, Jobert, and Montavont (2008) used behavioural and neuroimaging measures to test the perceptual expertise hypothesis. The hypothesis states that parallel processing of words in the visual word form area, part of the left ventral occipito-temporal pathway, is the result of years of extensive perceptual training. According to the perceptual expertise hypothesis parallel processing is not an inherent characteristic of the left hemisphere instead is acquired with practice and as such susceptible to the limitations of what it has been learned. Cohen et al., (2008) tested these limitations by comparing three modes of stimulus degradation – rotation, expanded letter spacing and displacement of stimuli into the left and right visual fields - with 5 degradation levels each. Centrally-presented French words of 4-6 letters in length were either presented horizontally or rotated clock- and counter-clockwise 22°, 45°, 67.5° and 90° from the horizontal plane. In a different condition, words were displaced to the left or to the right of central fixation, varying from 100% right of fixation, 50% right of fixation, central presentation, 50% left of fixation and 100% left of fixation. Behavioural results demonstrated a slowing down of RTs at 45°. A length effect was found only when words were presented 50 and 100% to the left of central fixation. For the neuroimaging data, rotation generated larger activation than either lateral displacement or letter spacing. Over occipito-temporal regions, hemisphere and rotation interacted such that the effect of rotation was larger in the LH than the RH. Analysis of the pattern of activity generated by rotated words demonstrated that activation increased as a function of rotation. The RH, whilst sensitive to stimulus degradation in general, was not specifically sensitive to word rotation.

Babkoff, Faust, and Lavidor (1997) also examined the effect of rotation on each of the visual fields. In this study, Hebrew words of between 3 and 5 letters in length were presented to the left and right visual fields. Words were rotated counter-clockwise in 15° increments, beginning at 0° and ending at 90°. For horizontal words (i.e. 0° rotation) and 15° rotated words, RTs were faster in the RVF than the LVF; for all other rotation angles, RTs were equal across visual fields. An unexpected finding was the absence of a main effect of length or an interaction of length with visual field or orientation angle. The lack of length by visual field interaction observed by Babkoff et al. (1997) supports the results found in Experiment 7 (Chapter 7) and may be attributable to the use of a language read in the opposite direction to English (i.e., right to left). Babkoff et al. (1997) concluded that above the critical angle of rotation – i.e. for rotation $>30^0$ – holistic word recognition processes are no longer possible and a more sequential, letter-by-letter type process is engaged.

In a follow-up study, Lavidor, Babkoff, and Faust (2001), presented words of three and six letters in length to the two visual fields, with seven different angles of orientation (from 0° to 90°). Orientation of the letters within words was also varied, such that letters could appear either upright or rotated with the word. Results showed an interaction of visual field and orientation, such that, for rotation <30˚, RTs to RVF words were faster than those to LVF words. For rotation >30˚, RTs in the two visual fields were highly similar. They also found a four way interaction in which word length did not differ significantly and the RVFA was reversed in some conditions (i.e., orientation angles above 60°). The orientation angle of the letters was also significant with slower responses to rotated words with upright letters. In a second experiment, words were primed such that, immediately prior to a target, a centrally-presented cue briefly appeared on-screen that indicated the orientation of the target. The orientation angle of the word was manipulated but this time at two levels: standard format (up to 30°) and non standard format (above 30°). Cues consisted of strings of Xs. Comparison of cued and non-cued trials indicated that cuing facilitated the recognition of words in 'standard' format (i.e. horizontal or rotated <30˚) in the RVF, such that the RVF advantage was larger for cued than uncued trials. For words in 'non-standard' format (those rotated >30˚), RTs in the left and right visual fields were equal. Whilst RTs were speeded in general, the results of Lavidor et al. (2001) suggest that the presence of a cue provided a LH benefit for words in standard format but not for those in non-standard format.

Lavidor et al. (2001) account for their findings within the lateralised word recognition model. The model claims that the adult LH, due to the constant exposure to written words, develops greater responsiveness for those words presented in standard formats. Thus, words in standard formats are quickly identified and processed by the semantic lexicon (route A). Words in non-standard formats have to be previously processed by a visual-orthographic mechanism (route B) before accessing the semantic lexicon. It is argued that the semantic lexicon (route A) is exclusively situated in the LH while the mechanism of route B is inclusive and available in the LH and RH. The model is strongly reminiscent of the dual mode model proposed by Ellis et al., (1988). In the dual mode model, it is further argued that processing occurs in parallel for route A and serially in route B. The model predicts the commonly-found length by visual field interaction in lateralised word recognition and this was not the case in Lavidor et al., (2001).

It is notable that the results of Babkoff et al. (1997) and Lavidor et al. (2001) – like those of Howell and Bryden (1987) – failed to find an interaction of length and visual field for horizontally-presented items. In the case of Babkoff et al. (1997) and Lavidor et al. (2001), the lack of interaction may be attributable to the use of Hebrew stimuli. This could cause a lack of effect for two reasons – firstly, as Hebrew is read right→left, visual field asymmetries may differ from those observed in English (as found in Experiment 7, Chapter 7). Secondly, as the most common form of written Hebrew (and the type used by Babkoff et al. and Lavidor et al.) consists only of consonants, it may be the case that word length has a different impact on the recognition of Hebrew words than on that of English words. By contrast, Howell and Bryden (1987) found that, in terms of RT, length and orientation interacted such that vertically-presented items showed larger length effects than horizontally-presented target. However, this interaction did not differ by visual field, indicating that both visual fields were equally affected by increasing word length and stimulus orientation.

Thus, while some studies report a RVF advantage for the recognition of words irrespective of their orientation (Bub & Lewine, 1988; Cohen et al., 1979; Young & Ellis, 1985), others have only found the RVF superiority for horizontal presentations (Howell & Bryden, 1987; Jordan & Patching, 2003). The influence of word orientation on the relationship between length and visual field remains also unclear. For vertical presentation, it has been suggested that vertical words presented in marquee format induce comparable length effects in both visual fields (Ellis & Young, 1985; Bub & Lewine, 1988). However, Lavidor et al., (2001) reported no length effects in either of the two visual fields on orientations above 60^0. Lavidor et al.'s (2001) is the only study to date that not only manipulated the orientation angle of the words but also the orientation of the letters in the word in addition to word length and visual field. No length effects were reported in this study. This might have been due to the noise introduced by including a language read from right to left (i.e., Hebrew).

The present chapter reports two experiments that investigated English word recognition processes in the two visual fields when words varied in string length and orientation angle. The orientation of the letters of those words presented vertically was also manipulated.

The lateralised word recognition model (Lavidor et al., 2001) and the perceptual expertise hypothesis (Cohen et al., 2008) argue that the ability of the LH to process words more effectively, or in parallel, is acquired with training. The two vertical presentations used in the present study might not be equally familiar to readers. This is because on occasions in which space is limited (e.g., book spines, tubes of cosmetics or tablets, etc) words are presented in a rotated format more often than in a marquee format. Thus, assuming that training with a script facilitates lexical and parallel processing, it is predicted that the recognition of words presented in marquee versus rotated would differ and potentially interact with word length. Byrne's (2002) supports this prediction since he found, in a study that only manipulated orientation angles, that marquee-presented words were processed slower and less accurately than rotated words.

Therefore, on the basis of previous findings, it is predicted that horizontal words will generate the fastest and most accurate responses. A length by visual field interaction should be present for horizontal words. For vertically-presented words, as they are not in standard format, it is predicted they will demonstrate length effects in both visual fields, although the magnitude of the length effect for marquee and rotated words might vary.

9.1 Experiment 10

9.1.1 Method

9.1.1.1 Participants

Thirty monolingual, native English-speaking students (12 male, 18 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 18-35 (mean age: 24). All were rated as strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £15 in return for their participation.

9.1.1.2 Materials

Three sets of experimental stimuli were developed. Each set contained 40 words and 40 non-words. Half of the words and half of the non-words were 4-letters in length, with the remaining half of each set being 7-letters long. Word sets were matched in terms of AoA and imageability (Stadthagen-Gonzalez & Davis, 2006) and written frequency (CELEX; Baayen, Piepenbrock, & van Rijn, 1993; WFG; Zeno et al., 1995). Given the difficulty of matching *N* across word lengths, words were matched for *N* across sets but within lengths, such that all three sets of 4-letter words were matched for *N* and all three sets of 7-letter words were matched for *N*.

Word length (short/long), visual field (LVF/RVF) and orientation (horizontal/marquee/rotated) were orthogonally manipulated, leading to 12 experimental conditions: (1) four-letter words, horizontal presentation, LVF; (2) seven-letter words, horizontal presentation, LVF; (3) four-letter words, horizontal presentation RVF; (4) seven-letter words, horizontal presentation, RVF; (5) four-letter words, marquee presentation, LVF; (6) seven-letter words, marquee presentation, LVF; (7) four-letter words, marquee presentation RVF; (8) seven-letter words, marquee presentation, RVF; (9) four-letter words, rotated presentation, LVF; (10) seven-letter words, rotated presentation, LVF; (11) four-letter words, rotated presentation, RVF and (12) seven-letter rotated words RVF.

9.1.1.3 Apparatus and Procedure

Three versions of the experimental program were created. Each version presented all three sets of words. In any given version, words sets were presented in one of three possible orientations: horizontal, marquee or rotated. Across the three versions of the program, word sets were rotated such that each set appeared in each orientation. Similarly, the order of orientation was counterbalanced across participants. Table 9.1 demonstrates word sets assigned to each version of the program.

Table 9.1. Example of counterbalancing of word orientation and word sets in Experiment 10

	Horizontal	**Marquee**	**Rotated**
Version 1	Set 1	Set 2	Set 3
Version 2	Set 3	Set 1	Set 2
Version 3	Set 2	Set 3	Set 1

All stimuli were presented in lower-case, monospaced Courier New font, size 30. As marquee words occupy slightly more space than their horizontal and rotated counterparts, care was taken to adjust the inter-letter spacing of words such that, as closely as possible, all words were the same physical size without distorting the configuration of the word. Stimuli appeared white against a black background to minimize screen flicker and were laterally displaced 2° from fixation. In the case of horizontally-presented words the last letter of LVF and the first letter of RVF stimuli were used for the point of displacement. For any version of the experiment, words from a given set appeared in one of three orientations and were presented twice, once in the LVF and once in the RVF. Trials were blocked by orientation and the order of presentation of blocks was counter-balanced across participants.

The experiment began with 48 practice trials (24 words and 24 non-words), different from those used as experimental stimuli but maintaining the same string lengths and orientations.

Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, target items were presented for 150ms in either the left or right visual field. The participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, an asterisk (*) appeared on-screen for 750ms. The next trial then commenced with fixation cross.

The importance of fixating on the cross during the task was emphasised in the pre-experimental instructions, as was the need for speed and accuracy. Trials were presented in blocks; at the end of a block, participants could take a short break. Trials recommenced upon a button press.

9.1.2 Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (2% of all trials). Seventeen percent of responses were participant errors and were rejected from subsequent analyses. Data from one participant was rejected from subsequent analyses due to a high error rate (>40% errors). Mean reaction times, standard deviations and accuracy rates for words and non-words are presented in Table 9.2.

Only correct responses were analysed. Four repeated-measures ANOVAs were conducted separately for RT and accuracy data for words and non-words by subjects (F_1). In these analyses, length (short vs. long), visual field (LVF vs. RVF) and orientation (horizontal vs. marquee vs. rotated) were within-subjects factors. Four by-items analyses (F_2) were also conducted on RT and accuracy data for words and non-words, with orientation and length as between-subjects factors and visual field as a within subjects factor.

Table 9.2. Mean (M), standard deviation (SD) and percentage accuracy (%Acc) for words and non-words as a function of orientation, string length and visual field.

		WORDS		
	LVF		RVF	
	Short	Long	Short	Long
		HORIZONTAL		
M	570	613	580	597
SD	120	117	161	154
%Acc	85	91	86	84
		MARQUEE		
M	687	724	685	772
SD	167	124	153	219
%Acc	77	55	76	50
		ROTATED		
M	621	697	620	696
SD	117	116	130	137
%Acc	83	66	85	71
		NONWORDS		
		HORIZONTAL		
M	631	646	637	634
SD	132	139	162	143
%Acc	90	91	86	92
		MARQUEE		
M	756	755	747	734
SD	166	192	164	149
%Acc	81	77	84	83
		ROTATED		
M	697	700	700	697
SD	120	142	120	123
%Acc	80	81	82	84

9.1.2.1 Responses to words

9.1.2.1.1 Reaction Time

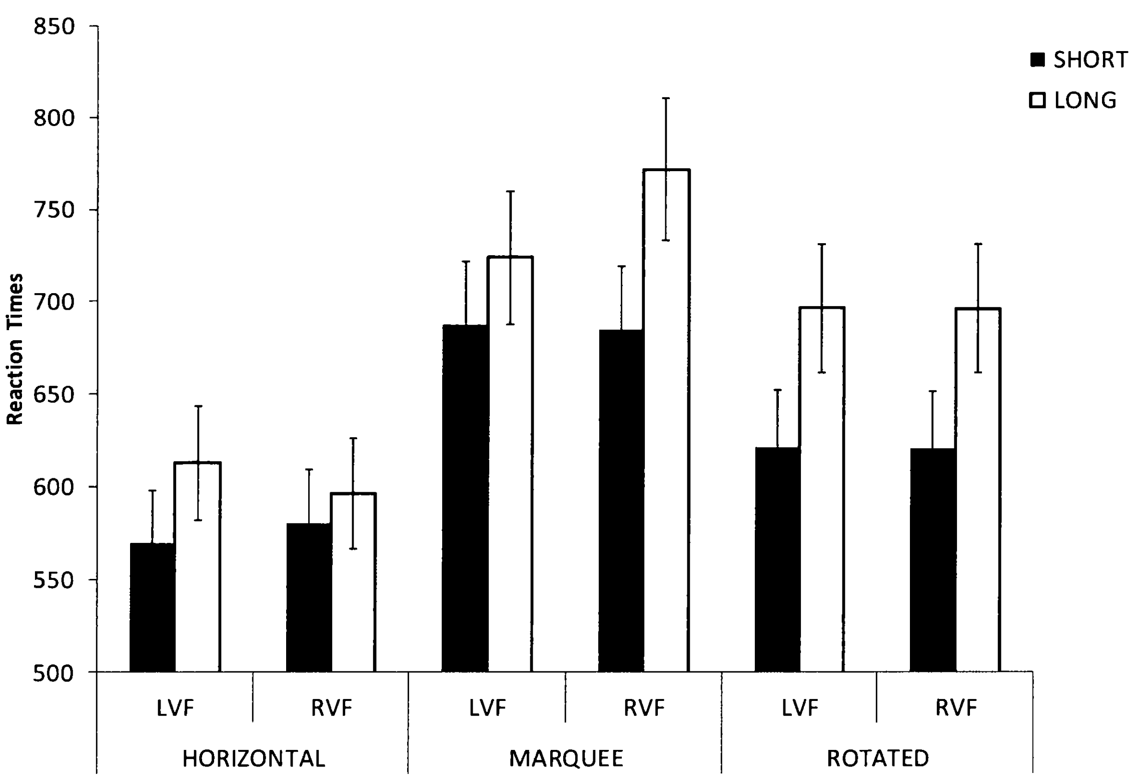
Two ANOVA analyses were carried out (by-subjects and by-items). Orientation, visual field and letter length were within subjects factors in the analysis by subjects while length was a between subjects factor and orientation and visual field a within subjects factor in the analysis by items. A main effect of orientation was evident in the RT data, by-subjects and by-items: $F_1(2,56) = 39.47$, MSe = 470646.21, $p < .001$, $\eta^2_p = .59$; $F_2(2,114) = 112.46$, MSe = 260082.03, $p < .001$, $\eta^2_p = .66$. Participants identified horizontal words most quickly (590ms), followed by rotated words

(658ms) and marquee words (717ms). The difference between all words types was significant at $p < .001$.

Lexical decision latencies were also affected by length: $F_1(1,28) = 116.82$, MSe = 269276.94, $p < .001$, $\eta^2_p = .81$; $F_2(1,114) = 72.89$, MSe = 168572.99, $p < .001$, $\eta^2_p = .39$. Short words (627ms) were recognized significantly faster than long words (683ms).

Finally, orientation, length and visual field interacted: $F_1(2,56) = 3.51$, MSe = 11174.41, $p < .05$, $\eta^2_p = .11$; $F_2(2,114) = 2.83$, MSe = 5147.36, $p < .05$, $\eta^2_p = .47$. The nature of the interaction was such that for horizontal words, a significant effect of length was present in the LVF (43ms; $p < .01$) but not the RVF (17ms; $p = ns$). For marquee words, this pattern was reversed: there was no statistically significant effect of length in the LVF (37ms; $p = ns$) and a large effect of length in the RVF (87ms; $p < .01$). Finally, for rotated words, a large effect of length (76ms in both cases; both $p < .01$) was evident in both visual fields. A graph of the interaction can be seen in Figure 9.2.

Figure 9.2. Mean RTs to words as a function of word length, visual field and orientation. *y*-axis is measured in milliseconds (ms). Asterisks indicate significant differences.



9.1.2.1.2 Accuracy

A main effect of orientation was evident in the accuracy data: $F_1(2,56) = 63.18$, MSe = 13908.91, $p < .001$, $\eta^2_p = .69$; $F_2(2,114) = 23154.16$, MSe = 1379120.88, $p < .001$, $\eta^2_p = .99$. Horizontal words (87%) were identified most accurately, followed by rotated (76%) and marquee (65%). The difference between each orientation was significant ($p < .05$).

Response accuracy was also affected by length: $F_1(1,28) = 63.39$, MSe = 13531.22, $p < .001$, $\eta^2_p = .69$; $F_2(1,114) = 156.68$, MSe = 3618.51, $p < .001$, $\eta^2_p = .58$. Short words (82%) were identified with significantly greater accuracy than long words (70%).

The interaction of orientation, length and visual field was significant by-items and marginally significant by-subjects: $F_1(2,56) = 3.54$, MSe = 198.56, $p < .05$, $\eta^2_p = .11$; $F_2(2,114) = 3.04$, MSe = 136.94, $p < .052$, $\eta^2_p = .51$. Post-hoc pairwise comparisons indicated that, for horizontal words, an effect of length was present in the LVF ($p = .006$) but not the RVF. For marquee words, an effect of length was present in the RVF ($p = .001$) but not the LVF. For rotated words, an effect of length was present in both visual fields (both $p < .001$).

9.1.2.2 Responses to non-words

9.1.2.2.1 Reaction Time

Response latencies to non-words varied as a function of orientation: $F_1(2,56) = 35.88$, MSe = 358742.96, $p < .001$, $\eta^2_p = .56$; $F_2(2,114) = 89.02$, MSe = 242987.49, $p < .001$, $\eta^2_p = .61$. Horizontal non-words were identified most quickly (637ms), followed by rotated non-words (698ms) and marquee non-words (748ms). The difference between each orientation was significant (all $p < .001$). No other main effects or interactions approached significance.

9.1.2.2.2 Accuracy

A main effect of orientation was evidence in the accuracy data: $F_1(2,56) = 14.76$, MSe = 2634.56, $p < .05$, $\eta^2_p = .15$; $F_2(2,114) = 29632.78$, MSe = 1703651.21, $p < .001$, $\eta^2_p = .99$. Horizontal non-words (90%) were identified significantly more accurately than either marquee (81%) or rotated (81%) non-words. Marquee and rotated non-words were recognized with equivalent accuracy.

Orientation and visual field interacted: $F_1(2,56) = 4.76$, MSe = 238.89, $p < .05$, $\eta^2_p = .15$; $F_2(2,114) = 4.51$, MSe = 164.73, $p < .05$, $\eta^2_p = .07$. For horizontal non-words, those presented to the LVF and RVF were recognized equally well (p = *ns*). For marquee and rotated words, RVF non-words were identified more accurately than LVF non-words (both $p < .05$).

Finally, VHF and length interacted: $F_1(1,28) = 4.92$, MSe = 241.67, $p < .05$, $\eta^2_p = .15$; $F_2(1,114) = 4.56$, MSe = 166.67, $p < .05$, $\eta^2_p = .04$. The nature of this interaction was such that short non-words were recognized equally well in both visual fields (p = *ns*). Long non-words were identified more accurately in the RVF (86%) than in the LVF (83%).

9.1.3 Discussion

The present experiment presented words of different lengths in one of three orientations – horizontal, marquee or rotated – to the left and right visual fields. It was predicted that horizontal words would demonstrate the well-established length by visual field interaction whilst words in non-standard format, which would be unable to take advantage of facilitated whole-word type processing in the LH, would demonstrate length effects in both visual fields. A potential difference between processing words in marquee and rotated orientations was predicted based on the idea that rotated words is a more familiar presentation format than marquee words.

The results of the analysis for words were clear. Across lengths and visual fields, horizontal words were identified fastest and most accurately, followed by rotated words then marquee words. This confirms the prediction that horizontal words are easiest to identify, with marquee words being most difficult, and is in agreement with Byrne (2002), who found similar results for centrally-presented words. This may be because vertically presented words in a rotated format are slightly more familiar than the marquee format but also because vertically-presented words in marquee format grossly violate the spatial relationship between letters within words. In keeping with this, long marquee words were particularly poorly recognised in both visual fields, with performance in both being just above chance. By contrast, rotated words retain the original configuration of a horizontal word and turn the whole word 90° clockwise. Thus, whilst rotated words were slower and less accurately identified than horizontal words, they may be easier to recognise than marquee words, which represent relatively large violations of the standard word form or shape.

The key finding of the present experiment was the three-way interaction of word length, orientation and visual field. As predicted, horizontal words demonstrated a robust length by visual field interaction, which was present in both the RT and accuracy analyses.

Contrary to prediction, marquee words show a reversal of the typical length by visual field interaction, demonstrating an effect of length in the RVF but not the LVF for both RT and accuracy. This suggests that disrupting the processing of words by changing from a standard to a non-standard, vertical format has a greater impact upon the LH than the RH. In keeping with this, for marquee words, the length effect in the LVF was 37ms and was non-significant. For horizontal words, the (significant) length effect was 43ms. Thus, as the differences between short and long words in the LVF were similar across horizontal and vertical orientations, it would seem that the reverse length by visual field interaction for marquee words is largely driven by the LH, where the length effect increased from a non-significant 17ms for horizontal words to a highly significant 87ms for marquee words. It has been argued that the left hemisphere is more sensitive to the format of presentation than the right hemisphere (Cohen et al., 2008; Lavidor et al., 2001). The interaction found between length and visual field for words presented to the RVF in a marquee format might have been the result of the greater sensitivity of the LH to standard formats. Thus, those words presented in the most disrupted format (marquee presentation) generated a length effect in the RVF but not in the LVF and were processed generally slower in the LH (728ms) than in the RH (705ms). It should also be noted that, across both visual fields, accuracy for vertically-presented words was

>75% for short words but fell to approximately chance level for long marquee words. This may mean that the results for long marquee words need to be interpreted with some caution.

These findings somewhat support those of Young and Ellis (1985) and Bub and Lewine (1988), in that the size of the LVF length effect was similar irrespective of whether a word was horizontally or vertically presented. However, whereas both Ellis and Young (1985) and Bub and Lewine (1988) found length effects of equal sizes for vertically-presented words (in marquee format) in both visual fields, in the present experiment, a large effect of length was present in the RVF but no length effect was evident in the LVF. This may be attributable to the poor level of accuracy to long marquee words or may reflect the fact that the length manipulation in the experiment presented above was larger (4 to 7 letters) than Young and Ellis (1985) manipulation.

Rotated words demonstrated an identically-sized length effect of 76ms in both visual fields. Similarly, RTs to short and long words in the two visual fields were highly similar (short LVF: 621ms; RVF: 620ms; long LVF: 700; RVF: 697ms). This strongly suggests that both hemispheres were equally affected by rotating a stimulus by 90°. Thus, it would seem that rotating a stimulus perpendicular to the horizontal cancels out the typically-observed RVF superiority for words and evokes effects of length in both hemispheres. This supports the results found by Howell and Bryden (1987), who showed larger length effects in vertically–presented words.

Contrary to the findings of Babkoff et al. (1997), Lavidor et al. (2001) and Howell and Bryden (1987), the present experiment identified a three-way interaction involving length, visual field and orientation. Specifically, the predicted interaction of length and visual field was identified for horizontally-presented words and a reverse interaction (with a length effect in the RVF but not the LVF) was found for marquee words. The present results may differ from those of Babkoff et al. (1998) and Lavidor et al. (2001) due to the fact that both studies used Hebrew words whereas the current study used English words. As previously noted, the effect of length may differ for Hebrew words as a) Hebrew is read right→left and b) they are commonly represented in a manner that excludes vowels, meaning the effect of length may differ between English and Hebrew words. Furthermore, Howell and Bryden (1987) used three levels of letter length in their analysis (4-letters, 5-letters and 6 letters), whereas the present study used only two (short and long). This operationalisation difference may have enabled the length effects to be detected in the current investigation whereas they were not in the study by Howell and Bryden (1987).

The general pattern of performance for orientation was also reflected in the results for the non-words, with horizontal non-words being identified faster and more accurately than rotated non-words, which were in turn recognised more rapidly and successfully than marquee non-words. The interaction of orientation and visual field in terms of response accuracy showed that, for horizontal words, performance in the two visual fields was equally accurate. This supports the findings of Jordan and Patching (2000), who also found RVF superiority for words but not non-words. Taken together, these findings suggest that the ability of the LH to rapidly identify lexical items in a holistic manner is limited to words in a familiar orientation. Marquee and rotated non-words both demonstrated superior accuracy in the RVF.

Thus, the results of the present experiment suggest that when recognising laterally displaced words, horizontal words exhibit the expected interaction of length and visual field, marquee words demonstrate a reverse interaction (which may or may not be attributed to the poor performance of long marquee words) whilst rotated words evoke similar reaction times and length effects in both visual fields.

The two modes of processing model proposed by Young and Ellis (1985) suggested that the serial processing characteristic of the right hemisphere might not proceed in a strict right to left manner but more likely in an 'ends-in' like manner. Experiment 11 was devised in order to improve performance and to test whether facilitating an 'ends-in' like manner of processing would improve the performance of vertically presented words in the right and left hemispheres.

9.2 Experiment 11

The present experiment used briefly-presented primes, consisting of the first and last letter of a subsequent target word. According to Ellis et al., (1988) and, to a certain extent, Lavidor et al., (2001), both hemispheres have access to Route B mode of serial processing. The mode is used by the left hemisphere for all non-words and words presented in non-standard formats. The right hemisphere is assumed to process all items through this route B mode. If this is the case, the presence of a first and last letter prime should facilitate all responses derived from route B (available to both hemispheres).

9.2.1 Method

9.2.1.1 Participants

Thirty monolingual, native English-speaking students (9 male, 21 female) participated in the experiment. All participants were students at Swansea University who had normal or corrected-to-normal vision and were between the ages of 19-29 (mean age: 24) All were rated as strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants received £15 in return for their participation.

9.2.1.2 Materials

Stimuli were those used in Experiment 10, the only difference being that each word was preceded by a prime. A prime consisted of the first and last letter of the target word. To avoid priming for length, primes were adjusted such that the distance between the first and last letter was equal whether the target was a 4-letter or a 7-letter word. As such, primes for 7-letter words were slightly shorter than the target and primes for 4-letter words were slightly longer than the target. An example of the primes is given in Table 9.3.

Table 9.3. Example of prime stimuli and experimental procedure used in Experiment 11. Primes were centrally-presented; targets were laterally-presented, either in the LVF or the RVF. Primes and targets could be presented either horizontally or vertically (i.e., marquee or rotated format)

	4-letter	7-letter
Prime (60ms)	a m	b s
Mask 60ms	######	######
Target (150ms)	atom	bounces

9.2.1.3 Apparatus and Procedure

The procedure employed was the same as that used in Experiment 10 with the addition of primes. Each trial commenced with a fixation cross appearing in the centre of the screen for 1000ms. After presentation of the fixation cross, a prime appeared in the centre of the screen for 60ms. The prime was then masked by a string of ###### for 60ms. The target item was then presented in either the left or the right visual field for 150ms. As in the previous experiment, the participant's task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing a key on a two-key response box. Half of the participants were instructed that the left key indicated a word response and the right key a non-word response. Response keys were reversed for the remaining participants. Once a participant had responded, an asterisk (*) appeared on-screen for 750ms. The next trial then commenced with fixation cross.

9.2.2 Results

Response times (RTs) of less than 150ms or more than 2.5 standard deviations from the mean were treated as outliers and removed from the analysis (2% of all trials). Seventeen percent of responses were participant errors and were rejected from subsequent analyses. One participant was rejected from subsequent analyses due to a high error rate (>35% errors). Mean reaction times, standard deviations and accuracy rates for words and non-words are presented in Table 9.4.

Table 9.4. Mean RT, standard deviation and % accuracy to words and non-words as a function of orientation, word length and visual field.

	WORDS			
	LVF		RVF	
	Short	Long	Short	Long
	HORIZONTAL			
M	501	550	472	492
SD	72	92	72	80
%Acc	87	87	90	88
	MARQUEE			
M	610	683	580	660
SD	111	143	105	144
%Acc	79	58	78	56
	ROTATED			
M	549	615	516	591
SD	83	86	85	99
%Acc	85	72	88	78
	NON-WORDS			
	HORIZONTAL			
	Short	Long	Short	Long
M	569	605	551	577
SD	97	104	88	80
%Acc	90	90	87	92
	MARQUEE			
	LVF		RVF	
M	666	671	641	665
SD	145	149	117	144
%Acc	86	81	84	82
	ROTATED			
	LVF		RVF	
M	626	654	615	656
SD	120	119	100	121
%Acc	84	84	83	86

Only correct responses were analysed. Four repeated-measures ANOVAs were conducted separately for RT and accuracy data for words and non-words by subjects (F_1). In these analyses, length (short vs. long), visual field (LVF vs. RVF) and orientation (horizontal vs. marquee vs. rotated) were within-subjects factors. Four by-items analyses (F_2) were also conducted on RT and accuracy data for words and non-words, with orientation and length as between-subjects factors and visual field as a within subjects factor.

9.2.2.1 Responses to words

9.2.2.1.1 Reaction Time

Reaction times to words were affected by orientation: $F_1(2,56) = 56.17$, MSe = 488202.16, $p < .001$, $\eta^2_p = .67$; $F_2(2,114) = 132.97$, MSe = 287891.94, $p < .001$, $\eta^2_p = .70$. Horizontal words (504ms) were identified fastest, followed by rotated words (568ms) and marquee words (633). The difference between each orientation was significant (all $p < .001$).

A main effect of visual field was also evident: $F_1(1,28) = 19.57$, MSe = 94946.34, $p < .001$, $\eta^2_p = .41$; $F_2(1,114) = 55.24$, MSe = 76874.24, $p < .001$, $\eta^2_p = .33$. Words presented in the RVF (552ms) were identified significantly faster than those in the LVF (585ms).

Word length also impacted upon response latency: $F_1(1,28) = 88.22$, MSe = 319190.75, $p < .001$, $\eta^2_p = .76$; $F_2(1,114) = 88.39$, MSe = 180545.37, $p < .001$, $\eta^2_p = .42$. Short words (538ms) were recognized reliably quicker than long words (599ms).

Finally, orientation and length interacted: $F_1(2,56) = 5.90$, MSe = 15258.62, $p < .005$, $\eta^2_p = .17$; $F_2(1,114) = 3.09$, MSe = 6710.84, $p < .05$, $\eta^2_p = .05$. This interaction is depicted in Figure 9.3.

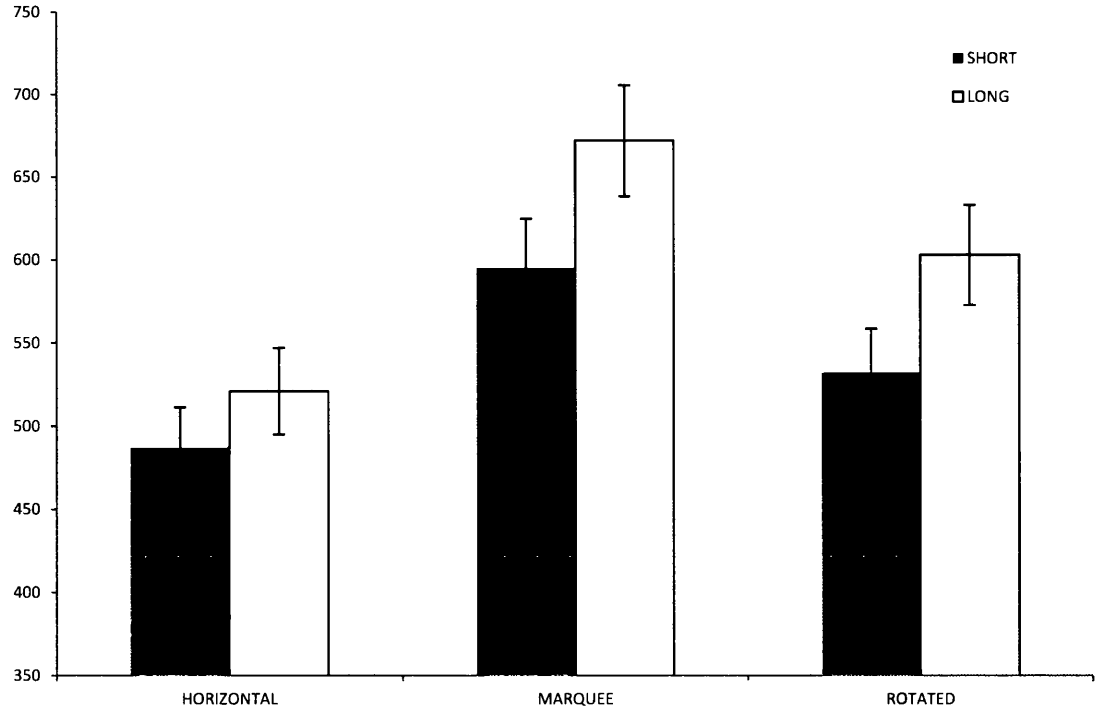


Figure 9.3 Interaction of word length and stimulus orientation. *y*-axis is milliseconds (ms).

Short words were identified faster than long words across all three orientations. However, the size of the length effect was smallest for horizontal words (34ms), larger for rotated words (71ms) and largest of all for marquee words (76ms). The difference between each orientation was significant (all $p < .001$).

9.2.2.1.2 Accuracy

Response accuracy was affected by orientation: $F_1(2,56) = 42.46$, MSe = 12306.97, $p < .001$, $\eta^2_p = .60$; $F_2(2,114) = 75.52$, MSe = 8487.56, $p < .001$, $\eta^2_p = .57$. Horizontal words (88%) were identified most accurately, followed by rotated (81%) and marquee (68%). The difference between each orientation was significantly different (all $p < .05$).

A main effect of word length was also present: $F_1(1,28) = 45.35$, MSe = 10814.94, $p < .001$, $\eta^2_p = .62$; $F_2(1,114) = 66.37$, MSe = 7458.58, $p < .001$, $\eta^2_p = .37$. Short words (84%) were identified more accurately that long words (73%).

Stimulus orientation and length interacted: $F_1(2,56) = 29.49$, MSe = 3313.87, $p < .001$, $\eta^2_p = .51$; $F_2(2,114) = 20.34$, MSe = 2285.42, $p < .001$, $\eta^2_p = .26$. Short and long horizontal words were recognized with equivalent accuracy (both 88%; p = *ns*). For marquee words, short words (79%) were recognized with greater accuracy that long words (57%; $p < .001$). The same was true of rotated words, where short words (86%) were again identified more accurately than long words (75%; $p < .001$).

Finally, a significant interaction of orientation and visual field was present by-subjects and by-items: $F_1(2,56) = 3.38$, MSe = 243.32, $p < .05$, $\eta^2_p = .41$; $F_2(2,114) = 4.78$, MSe = 167.81, $p < .01$, $\eta^2_p = .08$. For horizontal and marquee words, words were recognized equally well in the left and right visual fields. For rotated words, RVF-presented words (83%) were identified more accurately than LVF items (75%; $p < .001$).

9.2.2.2 Responses to non-words

9.2.2.2.1 Reaction Time

A main effect of orientation was evident in the RT data for non-words: $F_1(2,56) = 27.03$, MSe = 225920.75, $p < .001$, $\eta^2_p = .50$; $F_2(2,114) = 45.33$, MSe = 142292.78, $p < .001$, $\eta^2_p = .44$. Horizontally-presented non-words (576ms) were identified faster than rotated non-words (638ms), which were recognized faster than marquee non-words (661ms). The difference between each orientation was statistically significant (all $p < .001$).

Length affected responses to non-words: $F_1(1,28) = 14.88$, MSe = 62666.30, $p < .001$, $\eta^2_p = .35$; $F_2(1,114) = 11.28$, MSe = 35407.35, $p < .001$, $\eta^2_p = .09$. Short non-words (611ms) were responded to significantly faster than long non-words (638ms).

No other main effects or interactions approached significance.

9.2.2.2.2 Accuracy

Stimulus orientation significantly affected response accuracy to non-words: $F_1(2,56) = 13.26$, MSe = 1268.75, $p < .001$, $\eta^2_p = .32$; $F_2(2,114) = 9.53$, MSe = 875.00, $p < .001$, $\eta^2_p = .14$. Horizontal non-words (90%) were identified more accurately than both marquee non-words (83%) and rotated non-words (85%). Marquee and rotated non-words were recognized with equivalent levels of accuracy.

9.2.2.2.3 Comparison between unprimed and primed targets

To directly compare the effect that primes had on the processing of word length in each of the hemispheres, the results from Experiments 10 and 11 were compared in a 4-factor mixed ANOVA. Word length, visual field and orientation were within-subjects factors and the presence/absence of a prime was a between-subjects factor. Separate analyses were conducted for RT and accuracy.

9.2.2.3 Responses to words

9.2.2.3.1 Reaction Time

RTs to primed targets were significantly faster than those to unprimed targets: $F_1(1,56) = 9.69$, MSe = 1310715.98, $p < .005$, $\eta^2_p = .50$. Responses to RVF items were faster than to LVF targets: $F_1(1,56) = 4.96$, MSe = 30883.28, $p < .05$, $\eta^2_p = .10$. A main effect of orientation was also present: $F_1(2,112) = 92.95$, MSe = 958012.37, $p < .001$, $\eta^2_p = .62$, with responses to horizontal words (547ms) being faster than those to rotated words (613ms), which in turn were faster than those to marquee words (675ms). The difference between each orientation was significant (all $p < .001$). Finally, word length also influenced lexical decision latencies: $F_1(1,56) = 198.33$, MSe = 587407.77, $p < .001$, $\eta^2_p = .78$. RTs to short words (583ms) were significantly faster than those to long words (641ms).

The presence of the prime appeared to increase the superiority of the RVF in terms of RT. An interaction of visual field and prime [$F_1(1,56) = 10.86$, MSe = 67616.65, $p < .005$, $\eta^2_p = .16$] showed that for unprimed words, across lengths, RTs to unprimed words were equal in the LVF and the RVF. For primed targets, a clear RVF superiority was observed, with RVF target (552ms) being identified significantly faster than LVF targets (585ms; $p < .001$).

A three-way interaction of orientation, length and visual field showed that the effect of word length varied as a function of visual field and orientation: $F_1(2,112) = 4.23$, MSe = 11786.14, $p < .05$, $\eta^2_p = .10$. Across prime type, for horizontal words, increasing word length had a larger impact in the LVF than the RVF; short words were identified equally quickly in both hemispheres (p = *ns*) but long words were recognised significantly faster in the RVF than the LVF ($p < .001$). For marquee and rotated words, the hemispheres did not differ in terms of RTs to words of different lengths.

9.2.2.3.2 Accuracy

A main effect of orientation demonstrated that horizontal words (87%) were most accurately identified, followed by rotated words (78%), which in turn were followed by marquee words (66%): $F_1(2,112) = 102.21$, MSe = 26064.26, $p < .001$, $\eta^2_p = .65$. response accuracy also varied as a function of word length: $F_1(1,56) = 107.41$, MSe = 24270.26, $p < .001$, $\eta^2_p = .66$, with short words (83%) being identified more accurately than long words (71%). Orientation and length interacted: $F_1(2,112) = 59.72$, MSe = 8372.95, $p < .001$, $\eta^2_p = .52$, such that accuracy to horizontal words did not vary as a consequence of length. Marquee and rotated words both demonstrated robust effects of length in terms of response accuracy, with short words in both cases being identified significantly more accurately than long words.

Orientation also interacted with visual field: $F_1(2,112) = 6.932$, MSe = 565.77, $p < .001$, $\eta^2_p = .11$. For horizontal and marquee words, words were equally well identified across visual fields. For rotated words, RVF targets (80%) were identified more accurately than LVF items (76%; $p = .002$).

Finally, an interaction of orientation, length and visual field was apparent: $F_1(2,112) = 4.07$, MSe = 234.09, $p < .05$, $\eta^2_p = .07$. For horizontal words, a length effect was evident in the LVF but not the RVF. For marquee and rotated words, effects of length were apparent in both visual fields, with the difference between short and long words in both visual fields being larger for marquee words than for rotated words.

9.2.2.4 Responses to non-words

9.2.2.4.1 Reaction Time

Stimulus orientation affected RTs to non-words: $F_1(2,112) = 62.24$, MSe = 571253.48, $p < .001$, $\eta^2_p = .53$. Horizontal non-words were identified most quickly (606ms), followed by rotated non-words (668ms), which in turn were followed by marquee non-words (704ms). The differences between each word type were all significant (all $p < .001$). Responses to RVF targets (654ms) were faster than to LVF targets (665ms): $F_1(1,56) = 4.48$, MSe = 19149.84, $p < .05$, $\eta^2_p = .10$. Non-word length also modulated lexical decision latencies: $F_1(1,56) = 6.46$, MSe = 29511.56, $p < .05$, $\eta^2_p = .10$, with responses to short non-words (653ms) being faster than those to long non-words (666ms).

Non-word length and prime type interacted: $F_1(1,56) = 7.27$, MSe = 3210.95, $p < .01$, $\eta^2_p = .12$. Across orientation and visual field, short and long unprimed non-words were recognised with equivalent latencies. For primed targets, short non-words (611ms) were identified reliably faster than long non-words (638ms). Furthermore, the difference between primed and unprimed trials was significant only for short words, where short primed non-words (611ms) were recognised significantly faster than short unprimed non-words (695ms; $p < .001$). No other main effects or interactions approached significance.

9.2.2.4.2 Accuracy

Responses to non-words varied as a function of stimulus orientation: $F_1(2,112) = 27.49$, MSe = 3767.28, $p < .001$, $\eta^2_p = .33$. Horizontal non-words (90%) were recognised more accurately that marquee non-words (82%) and rotated non-words (82%). Marquee and rotated non-words did not differ in terms of response accuracy.

Orientation interacted with visual field: $F_1(2,112) = 3.34$, MSe = 149.39, $p < .05$, $\eta^2_p = .06$. In both visual fields, horizontal non-words (LVF: 90%, RVF: 89%) were identified more accurately than both marquee and rotated non-words. Marquee non-words (LVF: 81%; RVF: 82%) and rotated non-words (LVF: 83%; RVF: 83%) did not differ.

Finally, orientation and length interacted: $F_1(2,56) = 13.26$, MSe = 1268.75, $p < .001$, $\eta^2_p = .32$. For horizontal non-words, short targets (88%) were identified less accurately than long targets (91%; $p < .001$). For marquee non-words, the opposite pattern was observed: short non-words (84%) were identified more accurately than long targets (81%). Accuracy did not vary as a function of length for rotated non-words. No other main effects or interactions approached significance.

9.2.3 Discussion

The present experiment used briefly-presented primes to cue the first and last letters of target words of different lengths presented to the left and right visual fields. It was predicted that this priming would particularly facilitate the recognition of vertically presented words (i.e., marquee and rotated) assuming they are processed in the serial 'ends-in' manner characteristic of Route B and available to both hemispheres (Ellis et al., 1988; Lavidor et al., 2001)

The main findings of the present experiment do not support this prediction as there was no evidence to suggest that first/last letter primes facilitated recognition of rotated and marquee words (as measured by the presence absence of a length effect in each of the visual fields). The pattern of orientation effects was identical to that in the previous experiment; this confirms that horizontal words are most easily identified, followed by rotated words, which in turn were better recognised than marquee text. This was true across words lengths and visual fields. Non-words also conformed to the same pattern.

The finding of an interaction of orientation and length for primed targets suggests that, across visual fields, marquee words were most strongly affected by word length, followed by rotated words. This might offer some support for the perceptual expertise hypothesis (Cohen et al., 2008) and the lateralised word recognition model (Lavidor et al., 2001) since, as predicted, those words presented in the less unusual format from the two non-standard vertical presentations (i.e., rotated) were identified faster, more accurately and showed length effects of smaller size.

Horizontally-presented words were least affected by increasing word length. This supports the findings of Howell and Bryden (1987), who also identified an interaction of string length and orientation using horizontal and vertically-presented words.

9.2.3.1 Comparison between unprimed and primed trials

Comparison of data from primed and unprimed trials demonstrated that primed targets were identified faster but not more accurately than unprimed targets. Responses to primed RVF targets were an average of 90ms faster than their non-primed counterparts; for the LVF, primed trials were, on average, 68ms faster than unprimed targets. This suggests that whilst the presence of a first/last letter prime speeds lexical decision latencies, it does not impact upon the overall pattern of response accuracy. A main effect of visual field indicated that, across prime type, RVF trials were identified faster than LVF trials. This effect was qualified by an interaction of visual field and orientation, which showed than only primed trials demonstrated a RVF superiority. Thus, the presence of a prime seems to facilitate LH responses in general, in terms of reaction time, leading to a larger difference between hemispheres than in the unprimed condition. Moreover, an interaction of orientation, word length and visual field – similar to that observed in Experiment 10 – was also apparent. As this three-way interaction did not differ between primed and unprimed trials, it is highly likely that the effect of priming speeded responses but did not differentially affect one visual field or orientation over another.

9.3 General Discussion

The present chapter presented the results of two experiments that manipulated stimulus orientation – horizontal, vertical or rotated – in addition to word length and visual field. The experiments were identical except for the fact that the targets in the second experiment were preceded by a briefly-presented first/last letter prime.

In general, the results of the experiment confirm that facilitated, whole-word style processing, which is a feature of the LH when recognising frequently encountered words, is confined to horizontal (i.e. standard) orientation only. Changing the overall configuration of the word – by presenting the letters vertically or rotating it 90° clockwise – interrupted this facilitated processing and instigated comparable length effects in both visual fields. Processing was disrupted more by marquee presentation than by rotated, suggesting that not all non-standard format words are equally difficult to identify. In the present experiment, this might be because rotating a word through 90° keeps the overall 'shape' of the word intact, which may make it easier for individual letters to be identified i.e. as there might still be some supra-letter or word-level facilitation that assists sequential recognition of individual letters, even when 'normal' processing is disrupted. Marquee words – which represent an extreme violation of a word's standard format, were particularly poorly identified and, in the case of long marquee words, yielded a recognition probability of just above chance levels. It is interesting to note that the ease of processing words in the RH varied with presentation format showing fastest recognition for horizontally presented words, medium speed for rotated presented words and slowest identification of those words presented in a marquee format. This implies that the RH is also sensitive to the familiarity of the presentation format, albeit format familiarity did not alter the serial manner of processing. The nature of these processing differences in the RH would deserve further attention in future research.

Whilst priming facilitated LH responses in terms of RT and increased the RVF superiority, it did not differentially affect either visual field, word length or type of orientation. A parallel can be drawn between the results of the present study and those of Lavidor, Babkoff, and Faust (2001), who used a centrally-presented string of Xs to prime the orientation of subsequent target words presented to the left and right visual fields. Primes served only to speed response latencies and no significant priming effects were found for words than were in non-standard format. This suggests that knowledge of a forthcoming target's orientation does not allow either of the hemispheres to prepare itself to deal with rotation more efficiently than if it had not been primed. In the present study, knowledge of the first/last letter of a target did not assist either of the hemispheres in dealing with marquee and rotated words. This might imply that the serial strategy employed by mode B (in the RH and LH) does not strictly work in an 'ends-in' manner as suggested by Ellis et al., (1988).

Chapter 10: General Discussion

10.1 Introduction

This thesis described a series of experiments that investigated the right visual field advantage in visual word recognition. In particular, the present thesis focused on one commonly-employed method of eliciting the RVFA advantage – that of presenting words of different lengths to each of the visual fields. As reviewed in Chapter 2, studies wherein this method has been used (e.g. Bub & Lewine, 1988; Young & Ellis, 1985; Ellis, Young & Anderson, 1988; Iacoboni & Zaidel, 1996; Lavidor & Bailey, 2005; Lavidor, Ellis, Shillcock, & Bland, 2001) have yielded one particularly reliable finding: namely, that presenting words of different lengths to each of the visual fields results in an interaction of string length and visual field, such that an effect of length is typically observed in the LVF but not the RVF. Due to the partial crossing of the optic fibres at the optic chiasm, laterally-presented words project in the first instance to the hemisphere contralateral to the stimulated hemifield. On this basis, some authors have interpreted the interaction of length and visual field during the recognition of laterally-presented words as evidence that each of the hemispheres recognises printed words in qualitatively different ways, with the LH being able to recognise familiar words in a holistic, parallel-like manner and the RH being constrained to a more sequential, length-dependent manner of processing (Bub & Lewine, 1988; Ellis, 2004; Ellis, Young, & Anderson, 1988; Fernandino, Iacoboni, & Zaidel, 2007). Alternatively, others have argued that the length by visual field interaction can be explained either in terms of the perceptual training that develops during the course of becoming a skilled reader (e.g. Nazir et al., 2004) or in terms of hemisphere-specific activation patterns at the neural level (Whitney, 2001; Whitney, 2002).

Whilst the length by visual field interaction is a robust finding within the lateralised word recognition literature, little previous work has attempted to explore the neural basis of this effect. This is particularly surprising as many of the theoretical accounts that seek to account for the interaction of length and visual field propose hemispheric differences in the processing of words as the locus of the effect. As such, Experiments 1, 2, 8 and 9 of the present thesis represent the first systematic attempts at exploring hemispheric differences in the processing of words of different lengths using event-related potentials.

In order to address the question of whether processing in each of the hemispheres is essentially serial or parallel in nature, Experiments 3, 4 and 5 report the results of a novel application of neural and behavioural measures to investigate the impact of orthographic uniqueness point on the interaction of length and visual field.

A perceptual training account of visual field asymmetries proposes that the length by visual field advantage should be modulated by reading direction. This proposal was examined in Experiment 6.

Orthographic depth is a measure of the extent to which the phonology of the verbal form of a language is directly represented in its written form, with languages varying in the degree to which they can be considered orthographically transparent (with phonology being explicitly and unambiguously represented in orthography) or orthographically opaque (in which the relationship between graphemes and phonemes is not always clear and/or consistent). As it has been proposed that languages that differ in orthographic depth may be best read using different strategies (Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992; Ziegler & Goswami, 2005), the extent to which orthographic depth influenced the interaction of length and visual field was explored in Experiments 6-9. Additionally, as length effects have been shown to decrease with increasing reading experience in a given script (Aghababian & Nazir, 2000), and as bilinguals may differ in the level of reading experience they have in each of their languages, the extent to which bilinguals did/did not demonstrate an interaction in each of their languages was explored in Experiments 7-9.

Finally, in order to explore the extent to which each hemisphere is able to process words of different lengths that violate standard format, Experiments 10 and 11 present the results of a pair of experiments that manipulated the orientation of words presented to the visual fields.

The purpose of the present chapter is to summarise the main findings from the experimental work presented in the thesis. The implications of the findings for theoretical models that seek to account for the interaction of length and visual field will also be considered. A possible mechanism that seeks to account for both the existing body of evidence in addition to the evidence presented in this thesis will then be proposed. Finally, avenues for future possible research will be outlined, before concluding remarks are made.

10.2 Summary of the main findings

The neural basis of the word length effect in the left and right cerebral hemispheres

10.2.1Central Presentation

Experiments 1 and 2 sought to determine the effect of word length on the behavioural and electrophysiological responses of each of the hemispheres in monolingual English speakers. As noted in Chapter 4, previous behavioural studies that manipulated the length of centrally-presented words have reported variable effects, possibly as a result of variations in stimuli, task and paradigm. Furthermore, with the exception of Hauk and Pulvermüller (2004), little research has focused on the extent to which manipulating word length affects the electrophysiological response of each of the cerebral hemispheres. Therefore, in order to establish the effect of word length - both in terms of behavioural responses and on the neural activity induced in each hemisphere – Experiment 1 employed a lexical decision task in combination with centrally-presented 4- and 8-letter English words and non-words. Participants were monolingual English speakers. Behaviourally, it was predicted that participants would demonstrate a length effect for responses to words, as the length manipulation (4- letters and 8-letters) was relatively large. Furthermore, it was predicted that, in line with previous research, the effect of word length in the ERP waveform would change as a function of time. Finally, it was also predicted that if the LH N170 component is an index of lexical processing, a LH asymmetry for the N170 should be observed for words but not non-words.

In line with prediction, participants demonstrated a significant effect of length in terms of reaction time. In the ERP analysis, length elicited time-dependent effects, supporting the findings of several previous neuroimaging studies (EEG: Hauk and Pulvermüller, 2004; Hauk et al., 2006; Hauk et al., 2008; MEG: Assadollahi & Pulvermüller, 2001; Tarkainien et al., 1999). In particular, Experiment 1 demonstrated an effect of string length that varied as a function of time, with long words producing larger responses than short words at 100ms and short words being associated with greater activity than long words at 300ms. In the Discussion of Experiment 1, it was noted that this shifting effect of length closely reflected the results of Hauk and Pulvermüller (2004). However, in their study, Hauk and Pulvermüller (2004) were unable to rule out differences in luminosity between short and long words as the source of the early length effect at 100ms. The results of Experiment 1 in the present thesis contributed to understanding in this area by demonstrating that this early effect of length differentially affects words and non-words in each of the hemispheres. In the LH, at 100ms, amplitudes to non-words differed in terms of length, with long items generating larger amplitudes than short items; in contrast, amplitudes evoked in the LH by short and long words were equivalent at 100ms. In the RH, the opposite pattern was observed, with a marginally-significant length effect for words and no length effect for non-words. If, as Hauk and Pulvermüller (2004) suggest, the length-related activity at 100ms may be an artefact of the differing luminosities of short and long targets, it would be expected to be equal for both words and non-words alike. That this was not the case in Experiment 1 suggests that the early length-related effect observed at 100ms in the in the study by Hauk and Pulvermüller (2004) and in Experiment 1 in the present thesis reflects an early sensitivity to string length that differs across hemispheres and lexicality. In particular, the pattern of activity in the LH at 100ms, where amplitudes in the LH were sensitive to string length for non-words but not for words, is in general agreement with the findings of behavioural studies that have presented words of different length directly to each of the hemispheres, which typically indicate that length elicits larger effect on non-words than words. Clearly, it would be unwise to draw direct comparisons between such studies and the results of Experiment 1, being as a) Experiment 1 employed central – not lateral –

presentation and b) given the difficulties in interpreting how and the extent to which ERPs correspond to a given behavioural effect. However, it is interesting nonetheless that the pattern of activity observed at 100ms in Experiment 1 is in broad agreement with research that has suggested differential processing of words and non-words in the LH.

Furthermore, the results of the ERP analysis at 100ms support the findings of Hauk et al. (2006) and Hauk et al. (2008) in proposing that the early effect of length is generated in parieto-temporal-occipital areas. In Experiment 1, parieto-occipital sites were selected for inclusion in the ERP analysis both on the basis of previous findings (Bentin et al., 1999) but also after examination of topographic scalp maps that demonstrated that, for the time windows of interest, effects were maximal over parieto-occipital areas.

The pattern of responses on the N170 component provided clear evidence of differential activity across and within hemispheres in respect of words and non-words. In line with Maurer, Brandeis, and McCandliss (2005), the ERP analysis of Experiment 1 indicated that, independent of length, words demonstrated a greater leftwards asymmetry (as indexed by mean amplitudes) than non-words. For non-words, amplitudes recorded over LH and RH sites were statistically equal in magnitude. For words, amplitudes over the LH were significantly larger than those over the RH. This is also consistent with the findings of Hauk and Pulvermüller (2004), who identified larger LH than RH responses for the recognition of centrally-presented words.

Furthermore, at 170ms, lexicality and hemisphere interacted such that activity elicited by words and non-words peaked at different times in each of the hemispheres. In the LH, activity evoked by words peaked significantly earlier than that for non-words. By contrast, in the RH, activity generated by words and non-words peaked at statistically equivalent latencies. Taken together, these findings suggest that at ~170ms, processing of centrally-presented words is largely left-lateralised, with the processing of non-words appearing to elicit equal levels of activity in both hemispheres, suggesting that the processing of non-words may be similar across hemispheres. In addition, differences in the timing of peaks at 170ms indicated that processing of words and non-words differed in the LH, with words reaching peak activity significantly earlier than non-words. By contrast, no difference in the timing of word and non-word activity was detected in the RH. As such, these data support the view that centrally-presented words and non-words may be processed in different ways in each of the hemispheres, with the LH being particularly involved in the recognition of familiar words.

One striking finding of Experiment 1 was that no length effects were observed at 170ms. This is in contrast to Hauk and Pulvermüller (2004) and Van Petten and Kutas (1990), who both identified length-related effects between 150-260ms. The lack of length effects apparent in Experiment 1 may have been due to the time window selected for analysis – 130-230ms – which is larger than the 75ms used by Van Petten and Kutas (1990). Furthermore, Hauk and Pulvermüller (2004) used two time windows - 150-190ms and 210-260ms – to cover the period spanning the N170. As such, the lack of length effect at 170 in Experiment 1 may reflect a difference in the size of the time window selected for analysis.

There may be alternative explanations for the lack of length effects at 170ms. At 100ms, long words generated larger amplitudes; at 300ms, short words generated greater activity. As such, the effect of length changed as a function of time. Therefore, there was likely a point at which the activity produced by short and long words 'crossed-over', such that before that point, long words produced the greatest activity and, after that point, short words generated larger responses. If this is the case, the lack of length effects at 170ms may reflect the point at which this 'crossing-over' took place, meaning that averaging across the time window from 130-230ms yielded no net effect of length in terms of amplitude or latency.

A length effect re-emerged in the amplitude analysis at 300ms, with short words now generating larger amplitudes that their longer counterparts. This is consistent with previous research that has observed greater activity for short words in later time windows (Assadollahi & Pulvermüller, 2001; Hauk & Pulvermüller, 2004; Tarkainien et al., 1999). Hemispheric differences in terms of lexicality were again present at 300ms. In the LH, amplitudes to words and non-words differed; in the RH, words and non-words elicited amplitudes of equivalent magnitude. This again supports the proposition that words and non-words are processed in different ways by each of the hemispheres.

In summary, Experiment 1 demonstrated that, for centrally-presented words, increasing string length elicits different ERP responses in each of the hemispheres, supporting the contention that processing of words in the LH and RH is qualitatively different. Early differences in terms of length that had previously been reported were shown not to be a function of the increased luminosity of longer strings. Furthermore, Experiment 1 demonstrated that the LH is sensitive to the difference between words and non-words at 170ms and 300ms, suggesting that the LH processes words and non-words in different ways. By contrast, during the same time windows in the RH, words and non-words did not differ in terms of their magnitude or timing, strongly suggesting that the RH processes words and non-words in a similar manner. A main effect of length in the ERP analysis at 300ms supported the behavioural results, which also demonstrated at clear length effect in terms of reaction time.

10.2.2 Lateral Presentation

Previous behavioural studies that have used lateralized presentation of stimuli of varying length have typically identified an interaction of length and visual field, such that increasing word length has a larger impact upon the RH than the LH (Bub & Lewine, 1988; Ellis & Young, 1985; Ellis, Young & Anderson, 1988). Experiment 2 presented the results of the first study to systematically investigate the neural underpinnings of the length by visual field interaction in visual word recognition. Behaviourally, it was predicted that lateral presentation of words should influence the processing of LVF words more than of RVF words. The application of ERP measures to the DVF task permitted preliminary analyses to be undertaken that assessed the relative degree of success with which lateral presentation was successful in stimulating the intended hemisphere. It was predicted that if the paradigm was successful in stimulating the contralateral hemispheres, P1 and N1 amplitudes and latencies should be larger to contralateral targets than to ipsilateral targets. Furthermore, on the basis of previous work that has implicated the time window of 150-200ms as being key to the recognition of laterally-presented words (Barca et al., 2010; Cohen et al., 2000), it was predicted that the interaction of length and visual field would be presented in the ERP waveform at ~200ms.

The behavioural task was successful in demonstrating the predicted interaction of length and visual field. The nature of the interaction was such that increasing word length had a significantly larger impact upon reaction times in the RH than the LH.

Preliminary analyses of P1 and N1 components, that compared amplitudes and latencies to contralateral and ipsilateral presentations, indicated that the divided visual task employed in Experiment 2 was successful in stimulating the intended hemisphere. As such, subsequent analyses focused on the comparison of contralaterally-presented items only, so as best to make comparisons with behavioural data.

Between 130-230ms, amplitudes were larger for short words than for long words. Furthermore, the effect of length differed for words and non-words in each of the hemispheres, reflecting the behavioural finding of a length by visual field interaction. ERP amplitudes over the LH demonstrated an effect of length for non-words but not for words. The opposite was true in the RH, where a length effect was evident for words but not non-words. Whilst statistical comparison of waveforms from Experiments 1 and 2 was precluded due to the different topographic effects evoked by central vs. lateral presentation, it is nonetheless notable that this pattern of effects is highly similar to that observed in Experiment 1 for centrally-presented words and non-words at 100ms. Thus, it may be the case that, relative to central presentation, one effect of presenting words laterally is that patterns of activity may be slowed as compared to those evoked by centrally-presented words. This may be due to the fact that displacing words into the left and right visual fields causes a drop in acuity, which may mean processing takes longer to become established due to the reduced activity generated by laterally-presented words.

Between 180-280ms, amplitudes were larger for long words than for short words. In terms of latency, amplitudes to words and non-words were distinct in the LH, but similar in the RH. A similar pattern was identified in Experiment 1, at the N170 and P300 components. In Experiment 2, the effect occurred during the time window 180-280, which overlaps with both the N170 and P300 time windows used in Experiment 1. Thus, for both central and lateral presentation, words and non-words evoke different patterns of activity in the LH but not the RH. This further supports the suggestion that the LH is able to recognise words and non-words in different ways, whilst the RH is constrained to use a single form of processing that is applied to both words and non-words.

In the final time window, 280-380ms, amplitudes to long words were larger than those evoked by short words. As in Experiment 1, word length effects changed as a function of time. However, whereas in Experiment 1, long words generated larger responses early on, whilst short words evoked greater activity later in the processing cycle, for lateral presentation, the earliest length effect emerged at 130ms, at which time short words generated larger amplitudes than long words. At both the 180-280ms and 280-380 time windows, long words generated larger responses. Thus, although a time-dependent effect of length was again indentified in Experiment 2, the general pattern of this effect was the opposite of that observed in Experiment 1. This may be due to the reduced acuity of targets outside of central vision.

Experiment 2 represented a novel attempt to explore the neural basis of the length by visual field interaction in visual word recognition by using ERPs. The main finding of Experiment 2 was that the interaction of length and visual field demonstrated in the behavioural data was reflected in the electrophysiological data between 130-230ms, at which time amplitudes evoked by words in the RH varied as a function of word length whereas those in the LH did not. Furthermore, Experiment 2 found more evidence to suggest that each of the hemispheres processes words and non-words in different ways. Between 130-230ms, a length effect in terms of mean amplitude was present in the LH for non-words but not for words; in the RH, a length effect was apparent for words but not non-words. In general, this pattern was the same as that for centrally-presented words at 100ms. Furthermore, differences between each of the hemispheres in terms of how words and non-words are processed were also apparent between 180-280ms, at which time amplitudes to words and non-words differed in the LH but not the RH. As in Experiment 1, this pattern strongly suggests that each of the hemispheres processes words and non-words in different ways, with the LH thought able to apply two different modes of processing to words and non-words, whilst the RH has the capacity to engage just one mode of processing which it applies equally to words and non-words alike.

Thus, the results of Experiment 1 and 2 showed that word length exerted time and hemisphere-dependent effects on the processing of centrally- and laterally presented words. In particular, between 130-230ms, the pattern of activity in the LH in both Experiment 1 and Experiment 2 was similar, demonstrating an effect of length on amplitudes evoked by non-words but not words. Furthermore, results from both experiments strongly supported the finding that words and non-words are processed in different ways in each of the hemispheres. The 180-280ms time window in Experiment 1 and the 240-340 time window in Experiment 2 both demonstrated larger responses to words than non-words over the LH, with amplitudes in the RH being insensitive to lexicality. Taken together, the results of Experiment 1 and 2 strongly support the proposal that words and non-words are recognised by different mechanisms in each of the hemispheres. The implications of this finding for models that seek to account for the interaction of length and visual field will be discussed later in this chapter.

10.2.3 Orthographic Uniqueness Point: neural and behavioural effects in the LH and RH

Experiments 3, 4 and 5 sought to further address the question of whether each of the hemispheres recognises words in qualitatively different ways by manipulating word length and orthographic uniqueness point. The orthographic uniqueness point (OUP) of a word is the letter position at which, reading from left to right, the word becomes discriminable from all other possible matches in the mental lexicon. It was suggested that when processing of words occurs in parallel, OUP should demonstrate less of an effect than when processing is sequential. Given that it has been proposed that each of the hemispheres processes words in qualitatively different ways (e.g. Bub & Lewine, 1988; Ellis, Young & Anderson, 1988), Lindell, Nicholls and Castles (2003) and Lindell, Nicholls, Kwantes, and Castles (2005) presented 7-letter words with early and late OUPs to the left and right visual fields. On the basis of their findings, which demonstrated facilitation for early vs. late OUP words in both hemispheres, Lindell et al. (2003) and Lindell et al. (2005) argued strongly in favour of serial processing in both hemispheres. In response to these studies, Lamberts (2005) has suggested that both Lindell et al. (2003) and Lindell et al. (2005) failed to control their stimuli for total lexical overlap – that is, the number of letters-in-position shared by early and late OUP words – and that this may have created a confound in both experiments. Furthermore, an interesting question arising from the studies of Lindell et al. (2003; 2005) is how OUP interacts with the well-established interaction of word length and visual field. For example, if 7-letter early OUP words are recognized faster than 7-letter late OUP words, what will happen when a short word shares an OUP position with a longer word? Therefore, in order to explore the effect of OUP on the length by visual field interaction, Experiment 3, 4 an 5 presented early and late OUP words, of 4- and 7-letters in length to the central and lateral visual fields. Stimuli were matched for lexical overlap, as per the suggestion of Lamberts (2005). Experiment 3 sought to establish a behavioural effect of OUP for 7-letter centrally-presented words under lexical decision. ERP measures were also recorded from the LH and RH to gauge the influence of OUP in each of the hemispheres. Experiment 4 presented the same stimuli to the left and right visual fields for lexical decision, whilst Experiment 5 replicated Experiment 4 using a word naming task.

In order to establish the effect of OUP for centrally-presented words, Experiment 3 presented early and late OUP words to the central visual field for lexical decision whilst electrophysiological recordings were made. It was predicted that if processing is serial in nature, early OUP words would be identified faster than late OUP words. If processing is largely parallel in nature, it was predicted that the early and late OUP words would be processed with equivalent latencies. As Experiments 1 and 2 provided strong support for the proposal that each hemisphere processes words in a different manner, it was predicted that any OUP effect would be evident in the ERP data at 170ms.

Behaviourally, a clear effect of OUP was evident in the reaction time data; however, the nature of the effect showed that, contrary to prediction, late OUP words were identified both faster and more accurately than early OUP words. This surprising finding was reflected in the ERP data at 170ms, at which time late OUP words generated larger amplitudes over the LH than the RH, whilst early OUP words elicited voltages of equivalent magnitude in both hemispheres. Furthermore, analysis of peak latency indicated that, in the LH, late OUP reached peak activity significantly earlier than early OUP words. In the RH, early and late OUP words achieved peak activity at equivalent latencies.

Thus, contrary to prediction, Experiment 3 found behavioural and electrophysiological evidence to suggest that late OUP words are processed faster and more accurately than early OUP words, and that this reverse OUP effect seems to be driven by activity over the LH. Whilst unexpected, this finding is not without precedent. Miller, Juhasz, and Rayner (2006; Experiment 2), using a gaze-contingent sentence reading paradigm to explore the effects of OUP on parafoveal preview effects, found a small but consistent advantage for late OUP words across a range of eye tracking measures. It is notable that, as in Experiment 3, the stimuli employed by Miller et al., (2006) were controlled for total lexical overlap.

As such, the results of Experiment 3 do not obviously support either serial or parallel accounts of visual word recognition. Facilitation for late OUP words (in which the OUP occurred at or very near the end of the word) is compatible with an 'ends-in' scanning process that has previously been suggested as a form of sequential processing (Bradshaw, Bradley, Gates, & Patterson, 1978; Jordan, Patching, & Milner, 2000; Jordan, Patching, & Thomas, 2003). However, such a process would also be compatible with parallel processing models which also find an advantage for outside letters vs. mid-string letters (Ellis, 2004).

Centrally-presented words straddle fixation. Due to the position of OUP within the words, an early OUP typically fell at or near fixation, whereas a late OUP fell 3.5 character spaces to the right of fixation. Whilst there remains some uncertainty regarding whether the foveal area is bilaterally represented or only represented in the contralateral hemisphere, assuming the fovea is split along the vertical meridian offers a possible explanation of the results of Experiment 3. As a late OUP always fell in the RVF, it is possible that the portion of the word containing the OUP was also projected directly to the RH. For an early OUP, the OUP may either have been bilaterally projected or projected directly to the RH. Assuming that words are split and each half projected to the contralateral hemisphere, the word would probably be reassembled in the LH. If this is the case, it may be easier for the LH to re-integrate words when the portion containing the OUP has been directly received in the LH, rather than when the portion containing the OUP was initially projected to the RH.

Thus, the results of Experiment 3 indicated a clear behavioural advantage for late OUP words, both in terms of reaction time and accuracy, which was supported by the results of the ERP analysis. Moreover, the ERP analysis indicated that the difference between early and late OUP was driven by LH processing. As such, Experiment 4 presented the same 7-letter stimuli as Experiment 3 to the left and right visual fields. To explore the effect of OUP on the interaction of length and visual field, a new set of words was added to the design – 4-letter late OUP words. As such, 4-letter late and 7-letter early OUP words shared an OUP but differed in length. By contrast, 7-letter early and 7-letter late OUP words shared string length but differed in terms of the position of OUP within the word. On this basis, it was predicted that if processing is parallel-like in the LH, 7-letter early, 7-letter late and 4-letter late words would be recognised with equivalent speed and accuracy. In the RH, if processing was serial in nature, words with an early OUP would be recognised faster than words with a late OUP.

Experiment 4 presented words that varied in length and OUP to each of the visual fields for lexical decision. Behavioural measures of reaction time and response accuracy were taken. In the RVF, a length effect was found for 4-letter late and 7-

letter early words. Four-letter late and 7-letter late words were recognised with equal latencies. Thus, in the RVF, a length effect was induced when words varied in length but shared an OUP in an absolute letter position. No length effect was observed when comparing words of different length that shared an OUP in a relative letter position (in this case, the OUP was the final letter of the word). In the LVF, words that shared an OUP in an absolute letter position – 4-letter late and 7-letter early – were identified with equivalent latencies. Four-letter late OUP words identified faster than 7-letter late OUP words, reflecting the length effect typically observed in the LVF under conditions of lateral stimulus presentation.

Thus, the pattern of results from Experiment 4 confirms those of Experiment 3 by demonstrating that the LH is sensitive to OUP. Furthermore, as in Experiment 3, Experiment 4 provides behavioural evidence that suggests that late OUP words enjoy facilitated processing, relative to early OUP words, in the LH. As targets presented entirely in one of the visual fields project directly to the contralateral hemisphere, it is likely that this facilitation for late OUP presented in the RVF words is a property of the LH and not due to the splitting of the word across fixation. Furthermore, in addition to inducing a RVF length effect, Experiment 4 also extinguished the LVF length effect when comparing 4-letter late and 7-letter early OUP words. This suggests that, in the RH, processing proceeds in a sequential manner, proceeding from left to right, and that when the OUP is reached, processing is curtailed or has already reached a level of activation such that recognition of the target can take place. This would explain why 4- and 7-letter words – which would typically demonstrate a robust effect of length in the LVF – can be processed equally quickly in the LVF if they share an OUP.

The results of Experiment 4 suggest that OUP differentially affects each of the hemispheres. In the LH, the relative position of the OUP influenced processing more than the absolute letter position at which the OUP occurred. It may be the case that the fact that the OUP falls at or very near to the end of a word leads to the processing advantage enjoyed by late OUP words in the RVF. As with Experiment 3, this again may be compatible with an 'ends-in' scanning mechanism. By contrast, on the basis of the results of Experiment 4, the RH appears highly sensitive to the absolute position of OUP within a target, such that, when two words shared an OUP in an absolute letter position, they were recognised equally as quickly, irrespective of the length of the words. This finding suggests that length effects are not an inherent property of RH processing. However, the pattern of OUP effects observed in the LVF supports the view that processing in the RH is indeed serial in nature.

Experiment 5 replicated Experiment 4 using a word naming task with laterally-presented words. The results largely supported the findings of Experiment 4, by showing that, in the RVF, words with a late OUP were named equally fast, irrespective of length. Seven-letter early OUP words were named slower than 4-letter late and 7-letter late OUP words. In the LVF, 4-letter words were named faster that both early and late OUP 7-letter words. Thus, for word naming, the results for the LH supported those of Experiment 4 in suggesting that facilitation for late OUP words.

Taken together, the results of the three experiments presented in Chapter 6 strongly suggest that when stimuli are appropriately controlled, late OUP words are named faster and more accurately than early OUP words. Furthermore, the results of Experiment 3 suggest that, for centrally-presented words, this facilitation was late OUP words driven by LH activity. Presenting words directly to each of the visual fields to assess the impact of OUP on each of the hemispheres supported those of Experiment 3 by showing LH facilitation for long vs. early OUP words, with early OUP words of 7-letters in length being disadvantaged in terms of reaction time in comparison to 4-letter late and 7-letter early OUP words. This disadvantage caused a length effect to be induced in the LH. Results from the RH largely supported a serial account of processing. Finally, the results of Experiment 5 provided support for those of Experiment 3 and 4, by confirming that, the LH advantage for late vs. early OUP words persisted under conditions of word naming. Overall, the results of the experiments presented in Chapter 6 suggest that each hemisphere is sensitive to OUP but in different ways. This supports the view that each hemispheres processes words in a different manner.

10.2.4 Reading Direction and the length by visual field interaction

Perceptual training accounts of visual field asymmetries, such as Nazir, Ben-Boutayab, Decoppet, Deutsch, and Frost (2004) propose that the perceptual experience of learning to read greatly influences the manner in which readers perceive print. In particular, Nazir et al. (2004) have argued that during the course of becoming a skilled reader of a given script, a form of perceptual expertise develops such that areas of the retina that fall in the direction of reading become trained with written stimuli. Over time, the effects of this training are that printed words are recognised faster and more accurately at locations that fall in the direction of reading than those that do not. Such a perceptual training account makes a strong prediction about the direction in which print is read, as it proposes that the commonly-observed RVF advantage for left-tight scripts should be reversed for scripts that are read from left-right. Experiment 6 aimed to test this prediction[2].

In Experiment 6, native speakers of Hebrew – a language read right-left – performed lexical decision on two forms of written Hebrew words presented to the left and right visual fields. Word length was also manipulated. As they relate to reading direction, the results of Experiment 6 indicated no overall visual field asymmetry for Hebrew speakers during the recognition of laterally presented words. Furthermore, length effects of equal size were identified in both visual fields. These results were in agreement with Koriat (1985), who reported similar effects in terms of response accuracy (but not reaction time). However, the finding of a main effect of length in Experiment 6 conflicted with those of Koriat (1985) and Babkoff et al. (1996), who failed to identify reliable length effects in the visual fields. Thus, the results of the present study suggest that reading direction – and by consequence, the perceptual training that one gains during the course of learning to read – influences but is not sufficient to account for the RVF advantage. If it were, readers of right-left languages should have demonstrated a clear LVF advantage. The fact that this was not the case indicates that whilst reading direction has some influence over visual field asymmetries, factors other than left-right reading

[2] Experiment 6 also manipulated another variable – orthographic depth. The results of Experiment 6 as they pertain to orthographic depth will be discussed in the next section.

direction must account for the RVF advantage typically observed in task of visual word recognition.

10.2.5 Orthographic Depth and the length by visual field interaction

Experiments 6–9 enabled the effect of orthographic depth on visual word recognition in each of the hemispheres to be explored. Orthographic depth (Frost, Katz, & Bentin, 1987; Katz & Feldman, 1983; Katz & Frost, 1992) refers to the ease with which the phonology of a given script is reflected in its orthography. Moreover, orthographic depth is thought to influence the kind of reading strategy adopted by readers. For example, it has been proposed that readers of transparent orthographies – such as Welsh and Spanish – favour a reading strategy that focuses on small sub-word chunks, such as individual letters or bigrams, as these small units accurately reflect phonology. By contrast, readers of more opaque orthographies – such as English – tend to favour larger sub-word chunks such as rimes, as, given the relative inconsistency with which sounds are represented in print, reliance on small sub-word chunks does not always generate the correct pronunciation (Ziegler & Goswami, 2005).

Experiment 6 took advantage of one of the properties of the Hebrew language – namely, that it has two written forms, one orthographically transparent and one orthographically opaque – to explore the effect of orthographic depth on each of the hemispheres. Pointed script contains vowels and consonants and transparently represents the phonology of a word. By contrast, unpointed script consists largely of consonantal information only and is, thus, orthographically opaque as the pronunciation of an unpointed word is ambiguous. Given that each of the hemispheres is thought to recognise words in different ways, it was predicted that both hemispheres would show length effects for pointed script (i.e. as the optimal reading strategy is to rely on small, sub-word chunks, which would yield length effects in both hemispheres) but that only the RH will be sensitive to length differences for unpointed script (as unpointed words may be most efficiently read using a whole-word strategy, which may closely match the default strategy available in the LH)

The results of Experiment 6 demonstrated a main effect of script type, with unpointed words being recognised faster than pointed words. Contrary to prediction, no difference in the performance of the visual fields in respect of orthographic depth was observed for words. For non-words, an overall LVF advantage was observed, both in terms of reaction time and response accuracy. An interaction of non-word length, visual field and script type indicated that pointed non-words were subject to length effects in both visual fields and unpointed non-words demonstrated a length effect in the RVF not the LVF. Thus, the results of Experiment 6 were contrary to pre-experimental predictions in that no clear effects of orthographic depth were identified for words. Surprisingly, analysis of non-word data demonstrated a marked LVF advantage, with a lack of length effects for LVF unpointed non-words. This seemingly supports the reading direction account of visual field asymmetries. However, given that the advantage was for non-words, it is unlikely that participants would have become perceptually trained in reading non-words such that they would demonstrate facilitation for the processing of non-words over words. Therefore, the results of Experiment 6 offer only partial support for the effect of orthographic depth on hemispheric word recognition. It may have been the case that any such effects, were they present, may have been masked or mitigated by the use of a language read from right-left. To explore the influence of orthographic depth in left-right readers, Experiment 7 employed bilingual speakers whose two languages differ in terms of orthographic depth.

In Experiment 7, monolingual English speakers and bilingual English/Welsh speakers performed lexical decision on short and long words in English (monolinguals and bilinguals) and Welsh (bilinguals only) presented to the visual fields. The English/Welsh bilinguals who participated in Experiment 7 rated themselves as fluent in both languages; however, in all cases, English was their dominant language and Welsh – which is highly orthographically transparent – was rated as their non-dominant language. It was predicted that if the interaction of length and visual field is influenced by orthographic depth, bilinguals would demonstrate the advantage in English but not Welsh.

Analyses demonstrated that monolinguals and bilinguals demonstrated a comparable interaction of length and visual field. This is in line with the findings of Beaton et al. (2006), who, using a laterality index as a measure of visual field asymmetries, found that monolinguals and English/Welsh bilinguals displayed a LH advantage that of equal magnitude. Thus, it is likely that both groups did not differ in terms of the way in which they recognised words in each of the hemispheres, with a length effect in the LVF indicating serial processing in the RH and a lack of length effect in the RVF indicating processing was more parallel-like in nature.

When comparing bilinguals in each of their languages, as predicted, bilinguals demonstrated an interaction of length and visual field in English but not in Welsh. For Welsh, a length effect was observed in both visual fields, suggesting that recognition of Welsh words was carried out in a similar manner in both hemispheres. This finding is somewhat in agreement with those of Ellis and Hooper (2001) and Spencer and Hanley (2003), who found that developing readers of English and Welsh were more strongly influence by word length in Welsh than they were in English.

Thus, the findings of Experiment 7 suggest that orthographic depth can influence the interaction of length and visual field. However, another possible explanation for the results of Experiment 7 is that English was participants' dominant language and Welsh their non-dominant language. Therefore, it may be the case that, rather than orthographic depth, the results of Experiment 7 reflected participants' language dominance. To test this suggestion, bilinguals with a different pattern of language dominance – Spanish/English bilinguals – were recruited. Spanish/English bilinguals differ from English/Welsh bilinguals by virtue of the fact that their dominant language (Spanish) is orthographically transparent and their second language (English) is orthographically opaque. This is the opposite pattern to that presented by English/Welsh bilinguals.

10.2.6 Language dominance and the length by visual field interaction

Experiments 8 and 9 manipulated the length of words presented to bilinguals Spanish/English speakers in each of their two languages. From the results of Experiment 6 and 7, it was suggested that if orthographic depth influences the RVF advantage, Spanish/English bilinguals would show an interaction of length by visual field interaction for English but not Spanish. By contrast, is language dominance influences visual field asymmetries, it was predicted that participants would demonstrate an interaction of length and visual field for Spanish but not for English.

Experiment 8 presented short and long words in each of their languages to the left and right visual fields of bilingual Spanish/English speakers. Electrophysiological and neuroimaging measures were taken.

Behaviourally, bilinguals demonstrated an interaction of length and visual field in terms of response accuracy for English but not for Spanish. In English, short and long words were recognised equally well in the RVF, and short words were recognised more accurately than long words in the LVF. For Spanish, in both visual fields, participants were more accurate at identifying long words than short words. This is somewhat contrary to the notion of orthographic depth, which proposes that length effects should be more prevalent in orthographically transparent languages – such as Spanish – than they are in orthographically opaque languages such as English. Indeed, a length effect was observed for Spanish words in Experiment 8 – however, the nature of the effect was such that long words were recognised faster and more accurately in short words in Spanish, irrespective of visual field. This facilitation for long words was somewhat reflected in the ERP analysis at 280-380ms, at which time long words generated larger amplitudes than short words.

Although no explicit prediction was made about the comparative performance of bilinguals in each of their languages, an unexpected finding in Experiment 8 was that participants were behaviourally faster and more accurate at making lexical decisions to words in their non-dominant language – English – than they were in their dominant language, Spanish. This suggests that, in Experiment 8, bilingual Spanish/English speakers found it easier to make lexical decision to English words than to Spanish words. One possible reason for this is that, during the task, bilinguals may have been inhibiting their dominant language in order to perform well on their non-dominant language. Two well-known models of bilingual word recognition – the BIA model (BIA; Van Heuven, Dijkstra, & Grainger, 1998; BIA+; Van Heuven & Dijkstra, 2002) and the IC Model (Green, 1998) propose a role for inhibitory mechanisms in bilingual lexical access. It has been shown that bilinguals find it difficult to effectively 'switch off' one of their languages whilst performing a task in their other language (Kroll, Bobb, & Wodniecka, 2006). Thus, a mechanism is needed to effectively limit the interference of the non-target language on the target language. In both the BIA and IC models, inhibition is the mechanism that enables bilinguals to limit the effects of one of their languages on the other. In particular, the BIA model proposes that early processes in the recognition of printed words are not language-specific. As such, a word string could potentially activate word representations in either of a bilingual's languages. To limit this effect, the BIA proposes a layer of language nodes that provide top-down inhibition to word units, thereby limiting the possible interference effects of the non-target languages. Thus, in Experiment 8, given the very brief stimulus durations employed, it may be the case that early activity that activated features and letters in a non-language specific manner necessitated strong inhibition of Spanish in order for participants to be able to perform the task.

To follow-up the surprising finding of Experiment 8 – that is, that bilinguals were faster and more accurate to respond to targets in their non-dominant language than in their dominant language – Experiment 9 presented the same words to a different group of Spanish/English bilinguals for lexical decision. In Experiment 9, words were centrally-presented whilst EEG recordings were made. It was predicted that if the results of Experiment 8 were an artefact of lateralised presentation, then in Experiment 9, bilinguals would perform better in their dominant language than in their non-dominant language. If the tendency of participants for superior performance in their non-dominant language than in their dominant language was stable across tasks, it was predicted that bilinguals would show facilitated responses to English targets as opposed to Spanish targets.

Behaviourally, there was no main effect of language in Experiment 9, indicating that participants responded equally well in each of the languages. An interaction of length and language indicated that, as in Experiment 8, bilinguals were faster to response to long words than short words in Spanish. In English, short words were recognised faster than long. In terms of non-words, Spanish non-words were rejected faster and more accurately than English non-words.

The ERP analysis indicated that, at 100ms, amplitudes to English words were larger than those to Spanish words. This suggests that even at a relatively early stage of processing, activity generated in parieto-occipital areas was already diverging as a function of language. Furthermore, an interaction of language, length and hemisphere indicated that words and non-words were processed in difference ways in each of the hemispheres at 100ms. For Spanish, amplitudes did not vary as a function of length in either the LH or the RH. For English, amplitudes to long words were larger than those to short words in the LH; in the RH, amplitudes to short and long words were statistically equivalent. This supports the suggestion that words of different lengths are processed in different ways in each of the hemispheres. Furthermore, it supports the notion that orthographically transparent languages – such as Spanish – may use a similar strategy in the recognition of words and non-words.

This idea is also supported by the analysis of the N170 components. For Spanish, words and non-words alike elicited equivalent negativities over the LH. For English, words generated significantly more negative voltages than non-words. This supports the findings of Maurer, Brem, Bucher, and Brandeis (2005), who showed that words, non-words and consonant strings in German evoked N170s of equivalent sizes in the LH. By contrast, previous studies using native English speaking participants have shown that N170 responses to words are strongly left-lateralised, whereas non-words are not (Maurer, Brandeis, & McCandliss, 2005). Furthermore, analysis of peak latency at 170ms showed that, for English, activity generated by words peaked significantly earlier than that for non-words. The finding of a larger left hemisphere N170 for words than non-words in English was also identified in Experiment 1 of the present thesis, in which participants were monolingual English speakers. Finally, in Spanish, activity for words and non-words reached maximum at similar latencies.

The results of Experiment 9 suggest that the facilitated performance for bilinguals in their non-dominant language in Experiment 8 may have been an artefact of lateralised stimulus display. In Experiment 9, Spanish/English bilinguals demonstrated a behavioural length effect for English words, and a reverse length effects for Spanish words, where long words were identified faster than short words. In the ERP analysis, evidence was found that hemispheric processing of words differed by language. In particular, an early difference arose in amplitudes evoked by English and Spanish words at 100ms, suggesting that the word recognition system of bilinguals is sensitive to the differences between their two languages even at a very early stage of processing. At 170ms, English words demonstrated a larger LH N170 for English words than for English non-words; for Spanish, words and non-words evoked N170s of equal magnitude. This strongly suggests that words and non-words are recognised in different ways in each of the hemispheres. Furthermore, it suggests that words and non-words may be recognised with the same mechanisms in Spanish. This is consistent with the orthographic depth hypothesis, which suggests that for transparent orthographies, a focus on small-unit, sub-word chunks is most parsimonious. If this is true, it is likely that words and non-words in transparent orthographies would be processed in similar ways. This finding is supported at 170ms in the ERP analysis.

10.2.7 Format distortion and the length by visual field interaction

Experiments 10 and 11 sought to determine the effects of non-standard word orientation on the interaction right visual field advantage. For horizontal words, it is well-established that increasing word length elicits larger effects in the LVF than the RVF. However, in everyday life, we frequently need to read words that are presented in non-standard visual format. In addition to horizontal words, Experiments 10 and 11 considered the effect of two non-standard presentation formats – marquee and rotated – on the way in which words of different lengths are recognised in the two visual fields. It was predicted that both non-standard word formats would induce length effects in both visual fields, due to the fact that they violate the familiar word form. Given that rotated words are encountered (e.g. on book, CD and DVD spines) more often that marquee words (Byrne, 2002), it was predicted that marquee words would generate larger length effects than rotated words.

Experiment 10 presented horizontal, rotated and marquee words of different lengths to the left and right visual fields for lexical decision. A main effect of orientation demonstrated that, as predicted, horizontal words were identified most quickly, followed by rotated and marquee. The effect of length varied as a function of orientation and visual fields. For horizontal words, the predicted interaction of length and visual field was observed, demonstrating an effect of length in the LVF but not the RVF. Rotated words elicited a length effect of equal magnitude in both visual fields. Marquee words generated an effect of length in the RVF but not the LVF. Examination of the means for marquee words demonstrated that this interaction was largely driven by the poor performance of the LH with long marquee words. This suggests that marquee format words were particularly disruptive to LH processing. There is some support for this suggestion as Young and Ellis (1985) and Bub and Lewine (1988) have reported length effects for horizontal and marquee words that were of similar magnitude in the LVF, suggesting that the RH is relatively less sensitive to gross violations of a word's standard shape.

To explore the extent to which processing of words in each of the hemispheres proceeds in an 'ends-in' manner, Experiment 11 replicated Experiment 10 using first/last letter primes. It was predicted that if processing proceeds in an 'ends-in' manner, facilitation would be observed for words that have been primed with the first/last letter (relative to those that have not been primed). If processing proceeds in a serial manner, it was predicted that first/last letter primes would exhibit no facilitation compared to unprimed words.

Comparison of primed and unprimed trials demonstrated that the presence of a prime speeded lexical decision across all orientations but did not improve overall accuracy. Thus, as in Experiment 10, horizontal words were best identified, followed by rotated words and marquee words. Across visual fields, the effect of word length increased across orientation, with the difference between short and long being largest for marquee words, smaller for rotated words and smallest for horizontal words.

Comparison of primed and unprimed trials suggested that priming served to speed lexical decision latencies across visual fields but did not differentially affect visual fields or word orientation. Thus, the results of Experiments 10 and 11 do not offer strong support for an 'ends-in' scanning mechanism, and offer no support for such a scanning mechanism being present in one hemisphere as opposed to the other. This conclusion is based on the fact that priming targets with a first/last letter prime facilitated lexical decision in general but did not alter the global pattern of responding across visual fields, word length or orientation. Thus, the results of Experiment 10 and 11 support the findings of previous studies that have manipulated word format (e.g. rotation; Babkoff et al., (1997); Lavidor et al., (2001) in showing that the interaction of length and visual field is confined to words presented in a standard, horizontal format. Violation of the overall shape of a word – such as by rotating it or presenting its letters in an unusual configuration – is particularly disruptive to LH processing, which derives its facilitation from its ability to recognise familiar words in standard format in a holistic manner. This mode of processing is disabled when words are not presented in standard format.

10.3 Methodological Issues

With the exception of Experiments 1, 3 and 9, the experiments in the present thesis employed the divided visual field task (DVF). In a typical DVF, participants fixate a central point or cross whilst targets are briefly represented to the left or to the right of fixation. In order for laterally-presented targets to stimulate the intended hemisphere, it is imperative that participants' gaze is centrally-fixated during trials. This is necessary, as, if fixation shifts, parafoveal targets may become foveally represented, making it difficult to know if a given target was projected to the intended hemisphere. In particular, it was noted in Chapter 3 that some authors have questioned the ability of participants to maintain central fixation on the basis of instruction alone (e.g. Jordan, Patching, & Milner, 1998; Jordan, Patching, & Thomas, 2003). As this is the most common method of ensuring fixation during DVF tasks (Bourne, 2006), clearly, the issue of how successfully the DVF paradigm delivers stimuli to the intended hemisphere is key to establishing its validity.

Whilst the EEG system employed in the present thesis did not directly monitor eye movements, as lateral saccades are visible in the EEG signal, any trials on which a significant lateral eye movement occurred was rejected from the ERP analysis. Thus, trials considered for analysis were those during which no significant shift in gaze occurred. As such, the patterns of activity analysed in Experiments 1 and 8 involved trials that were not contaminated by eye movement artefacts. One drawback of this method is that the absolute position of gaze cannot be determined prior to the onset of a trial – as it can be using explicit on-line eye-tracking methods. Thus, in Experiments 1 and 8, if a participant fixated the central cross, then made a lateral saccade towards a target, the trial was rejected from subsequent analysis. However, if, as the trial began, the participant was fixating a non-central location, providing no significant eye movement occurred, the trial would be included in subsequent analyses. As such, whilst trials during eye-movements occurred were rejected, it may have been the case that some of the trials included for analysis featured non-central fixation. However, given the relative success of the paradigm in stimulating the intended hemisphere (see below), it is likely that such trials were few in number and exerted little overall influence on the patterns of results observed.

Using EEG, previous research has shown that, when stimuli are efficiently directed to the intended hemispheres, P1 and N1 components should be larger/faster over the hemisphere contralateral to the stimulated hemifield (Doyle & Rugg, 1998). In the present thesis, Experiments 2 and 8 employed a DVF task in conjunction with EEG recordings. In these experiments, preliminary analyses of contralateral vs. ipsilateral patterns of activity, for the P1 and N1 components, were able to shed light on the success with which the DVF task stimulated the intended hemispheres. In both experiments, results of preliminary analyses indicated that P1 latencies were faster for contralateral vs. ipsilateral presentation. Similarly, patterns of N1 activity also demonstrated this effect, with responses to contralateral targets being larger and faster than those for ipsilateral targets. Thus, in the present thesis, it is likely that the DVF method was relatively successful in stimulating the intended hemisphere.

10.3.1 Implications for current models of visual field asymmetries

The present thesis explored the neural and behavioural effects of the interaction of length and visual field in visual word recognition. The implications of the results of the present thesis on models that seek to account for visual field asymmetries during the recognition of printed words will now be discussed.

The present thesis found several lines of evidence to suggest that there are two distinct modes of processing, and that these modes of processing may be differentially employed by each of the hemispheres (Ellis, 2004; Ellis, Ferreia, Cathles-Hagan, Holt, Jarvis, & Barca, 2009). Evidence from EEG studies of laterally-presented in the present thesis suggested that the LH and RH hemispheres were differentially sensitive to short and long words and non-words. In particular, the early P1 activity observed in Experiment 2 strongly reflected the typical length by visual field interaction observed in behavioural studies (e.g. Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988), in which a length effect is observed for LVF targets but not for RVF targets.

10.3.2 Direct access or callosal relay?

It was noted in Chapter 2 that models that seek to account for visual field asymmetries tend to fall into one of two categories – direct access models or callosal relay models. Direct access models (e.g. Fernandino, Iacoboni, & Zaidel, 2007; Ellis, Young, & Anderson, 1988) propose that, during word recognition, each hemisphere operates independently of the other. Under such an account, LVF targets are recognized by the RH and vice versa for RVF/LH targets. Thus, direct access model propose that the poorer performance of the LVF (as compared to the RVF) is due to the RH being less efficient at carrying out lexical processing than the LH. In respect of the interaction of length and visual field, direct access models assume that, in the LH, processing proceeds in a manner that is relatively insensitive to string length, yielding no overall effect of length, whilst, in the RH, it is suggested that processing is highly sensitive to the number of words in a string.

By contrast, callosal relay models (e.g. Cohen et al., 2000; Nazir, 2000; Nazir et al, 2000, Whitney, 2001; 2002) propose that the superiority of the LH for language tasks is such that the RH depends upon the LH for all linguistic processing and that the RH has little – if any – capacity of its own to process written words (Weems & Reggia, 2004). Thus, callosal relay models suggest that the LH has overall responsibility for the processing and recognition of written words, irrespective of where the word was presented in the visual field.

The ERP findings of Experiment 2 and Experiment 8 confirmed that laterally-presented targets project, in the first instance, to the contralateral hemisphere. Furthermore, Experiment 2 demonstrated an early dissociation between words and non-words of different lengths in each of the hemispheres on the P1 component. Given that the P1 represents the earliest electrical marker that a stimulus is being received in a given hemisphere, it is likely that the early length and lexicality differences observed at 100ms reflect the characteristics of the hemisphere receiving the stimulus. Thus, patterns of activity at 100ms may represent the processing of targets independently in each of the hemispheres, suggesting that each hemisphere differs in respect to the very early stages of processing it employs during the recognition of written words and non-words. This supports the direct access model, at least in terms of the very early stages of processing, in suggesting that each of the hemispheres differs in terms of the way words and non-words of different lengths are processed. In Experiment 2, LH amplitudes to non-words were modulated by length, whereas those to words were not. In the RH, amplitudes varied as a function of length, whereas non-words did not. Thus, ERP data from the very early stages of processing support direct access models in suggesting that each hemisphere is differentially sensitive to the effects of word length and lexical status.

Several experiments in the present thesis offer support for the callosal relay model. Experiments 1 and 9 (English condition), which both employed centrally-presented words, show a clear asymmetry occurring at or around 170ms, in which amplitudes generated by word targets become strongly left-lateralised. By contrast, amplitudes evoked by non-words do not demonstrate a leftward asymmetry and are, instead, equivalent across hemispheres. Thus, whilst initial stages of processing may occur in line with direct access models (see above) it is likely that at or around 170ms, the processing of centrally-presented words becomes focused in the LH. This supports the callosal relay model, in that it suggests that processing of familiar words (but not non-words) becomes strongly left-lateralised at an early stage.

For lateralized words, if and when processing might become left-lateralized is less obvious. As noted earlier in this chapter, comparison of Experiment 1 and Experiment 2 demonstrated that an early length effect in terms of amplitudes was present in the LH for words but not for non-words. However, for Experiment 1 (central presentation) this effect occurred earlier (within the time window of the P1 component) than in Experiment 2 (where it was evident on the N1 component). Therefore, presenting targets laterally may fundamentally change the time at which LVF/RH targets are transferred to the LH (presuming that that is, indeed, the case). It may be the case that, for centrally-presented words – where each hemisphere may only receive half of the word - information from the RH must be transferred to the LH in order for the entire word to be recognized. For lateral presentation, where the entire stimulus is presented directly to a hemisphere, it may be the case that processing only becomes left-lateralised for LVF/RH targets later in the processing stream than for centrally-presented words.

Thus, the ERP experiments in the present thesis suggest that, in the case of laterally-presented words, initial processing is carried out in the hemisphere contralateral to the stimulated hemifield. By contrast, centrally-presented words invoke strongly left-lateralised processing, suggesting heavy LH involvement in the recognition of centrally-presented words. As such, the ERP experiments in the present thesis offer support for both the callosal relay and direct access models. It may be the case that displacing a target word – from the central visual field to the peripheral visual fields – may cause a change in the way processing is balanced across the hemispheres, with lateral presentation inducing greater hemispheric independence (at least for the early stages of processing) and central presentation inducing a greater reliance on the LH. However, this is one possible interpretation and it is noted that other interpretations are possible. Further research is needed to more fully explore whether hemispheric processing of words operates in a callosal relay or direct access manner.

10.3.3 Two modes or perceptual training?

Two prominent theories that have sought to account for the interaction of length and visual field in visual fields are the two modes of processing model (Ellis, Young & Anderson, 1988; Ellis, 2004) and the perceptual training model (Nazir et al. (2004). Each of these theories suggests that visual field asymmetries arise for different reasons.

In the case of the two modes model (Ellis, Young & Anderson, 1988; Ellis, 2004), it is suggested that there are two modes of processing: Mode A and Mode B. Mode A processing is driven by a parallel-like mechanism that enables rapid parallel-like identification of the letters in a target and Mode B by a more sequential (but not necessarily serial) mode. The two modes model suggests that the LH has access to both Mode A and Mode B processing, with words being recognised via Mode A and unfamiliar words and non-words via Mode B. In the RH, it is proposed that processing for words and non-words alike is driven by Mode B, meaning that a length effect is always evident during the recognition of LVF/RH targets. Thus, according to the two models model, the difference between hemispheres in terms of how word length impacts upon processing is driven by the differential availability of Mode A and Mode B processing in each of the hemispheres.

The perceptual training account (Nazir et al., 2004) proposes that the differing effect of word length identified in each visual field is a function of the perceptual expertise with a given script that develops over the course of becoming a skilled reader. Given the tendency of readers to fixate near word beginnings (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984), during the course of learning to read, readers become perceptually trained in dealing with larger variations in word length to the right of fixation than to the left. Nazir et al. (2004) propose that this perceptual expertise may drive the interaction of length and visual field.

In the present thesis, the ERP findings of Experiments 2 and 8 support the two modes theory, in that early, hemisphere-specific patterns of activation were observed. This suggests that – at least for the very early stages of processing – each of the hemispheres processes words in a different manner. Given the differing abilities of the LH and RH to use the proposed Mode A and Mode B, the two modes theory predicts that string length should differentially affect LH but not RH processing. The present thesis found evidence to support this pattern in Experiment 2. In Experiment 2, between 130-230ms, amplitudes to LH non-words varied by length whereas those to short words and non-words did not. Furthermore, between 180-280ms, in the LH, activity generated by words peaked earlier than generated by non-words. In the RH at the same time, words and non-words peaked at statistically equivalent latencies. These findings support the notion that each of the hemispheres processes words and non-words differently.

Some support was found for the perceptual processing account. In Experiment 6, it was shown that native Hebrew speakers demonstrated length effects in both visual fields and no overall visual field asymmetry. If perceptual training alone accounted for the RVF advantage typically observed in left-right readers, readers of a right-left script should demonstrate a LVF advantage. This was not the case in Experiment 6. However, the fact that no RVF advantage was observed either suggests that the perceptual training that reading direction induces during the course of learning to read can modulate visual field asymmetries. Furthermore, the early difference between words and non-words between 130-230ms in the LH may be explained by a perceptual training account, as commonly encountered short and long words demonstrated no variation in the size of amplitude between 130-230ms, whereas amplitudes generated by non-words varied as a function of length. This early difference in words and non-words across hemisphere may reflect the perceptual training proposed by Nazir et al., (2004), as under such an account activity induced by words of different lengths (which have become highly trained on the retina) show no difference in amplitudes whereas non-words of different length (which, as non-words, are untrained stimuli) differ with length.

In summary, the present thesis presents evidence in support of both the two modes model (Ellis, Young & Anderson, 1988; Ellis, 2004) and the perceptual training hypothesis (Nazir et al., 2004). It is possible that the two are not mutually exclusive – it is possible that hemispheric differences in terms of modes of processing could exist in tandem with a form of perceptual training that favours RVF responses to words of different lengths for left-right readers. Further research could explore this possibility.

10.4 Future Directions

The present study demonstrated the successful application of the ERP method in exploring the neural hemispheric differences in the processing of words. However, one of the limitations of using ERPs is that they are limited in what they can reveal about the neural generators of scalp-recorded potentials. As such, to further explore the neural basis of the interaction of length and visual field commonly observed in behavioural tasks using electrophysiological means, future work could employ source localisation methods (e.g. BESA, 2010). For any given set of scalp potentials, source localisation can model a range of possible solutions to the inverse problem using sets of dipole generators. In source localisation, modelling is user-constrained, in that it is guided by *a priori* knowledge about from roughly where in the brain activity associated with a given process or event may be generated. The localisation process begins with a single dipole, which the source localiser uses to compute the pattern of activity the single dipole would generate at the scalp. This pattern is compared with the pattern of activity from the experimental data and the amount of variance explained by the model is calculated. Further dipoles are added and the source localiser adjusts the model to best fit the observed data. Thus, source localisation allows an iterative fitting of a potential dipole model to the observed pattern of scalp-recorded potentials. However, even when a model achieves a good fit with experimental data, the model remains just one potential way in which the activity observed at the scalp may have been generated. There may be an infinite number of models that would explain the experimental data equally well, if not better. Despite this, source localisation models offer a potential way of exploring the neural generators of the interaction of length and visual field.

The present thesis presented the results of a set of experiments that explored hemispheric processing of words using behavioural and electrophysiological methods. In general, the length by visual field advantage was replicated across several experiments, substantially adding to the existing body of knowledge in this area. The use of event-related potentials in the present thesis represents the first systematic investigation of the interaction of length and visual field using neuroimaging measures. The results of these investigations strongly suggest that the hemispheres generate differential patterns of activity during the processing of written words, particularly during the early phases of processing, suggesting that processing of words and non-words carried out in each of the hemispheres may be substantially different. Chapter 6 demonstrated that each of the hemispheres may be differentially sensitive to the effect of orthographic uniqueness point. The findings of the experiments in Chapter 6 contribute to understanding in this area by showing that when stimuli are appropriately controlled, late OUP words are identified faster and more accurately than early OUP words and that this effect if largely driven by LH activity. Furthermore, the finding that OUP elicits differing effects on words of different lengths in each hemisphere may explain why previous studies have reported mixed effects when manipulating OUP in each of the visual fields (e.g. Lindell, Nicholls, and Castles (2003); Lindell, Nicholls, Kwantes, and Castles, 2005). In the Discussion of Chapter 6, it was noted that one explanation of the LH OUP effect involved 'ends-in' scanning. Chapter 9 explored the possibility of an ends-in scanning mechanism using laterally-presented words of various orientations but found little evidence to support such an account. Therefore, given the findings of Chapter 6 and Chapter 9, further word concerning the existence of a possible ends-in scanning mechanism is warranted. Lastly, the present thesis provided evidence for the role of orthographic depth in hemispheric words recognition. In Chapters 7 & 8, bilingual speakers demonstrated an interaction of length and visual field for orthographically opaque but not orthographically transparent languages. It was further shown that this effect was not due to language dominance. As such, these findings suggest that the interaction of length and visual field may be modulated by the orthographic depth of a given script.

Finally, one key aspect of the present thesis lies in its use of a variety of methods, paradigms, stimuli and participants with which hemispheric processing of words and the interaction of length and visual filed were explored. In particular, the present thesis provided substantial behavioural investigations of hemispheric asymmetries in visual word recognition which were supplemented by the use of event-related potentials. This approach enabled an examination of on-line processing that revealed patterns of hemispheric activity that cannot typically be discerned using standard behavioural measures.

10.5 Concluding Remarks

The present thesis set out to explore the neural and behavioural effects of word length on the hemispheric processing of individually-presented words. In doing so, it provided the first systematic investigation of the neural origins of the interaction of length and visual field typically observed in lateralised lexical tasks, the results of which suggest hemisphere-specific differences in the processing of words and non-words of different lengths. Furthermore, this thesis presented a body of behavioural work that supported the conclusions of the ERP studies, in suggesting that word length differentially affects the two cerebral hemispheres. As a whole, this thesis contributes to the body of knowledge in respect of visual word recognition by presenting behavioural and neural evidence that word length differentially affects each of the cerebral hemispheres.

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Appendices

Appendix A

Language skills questionnaire

Participant code: ....

Age: ....

Sex: ....

How many languages do you speak? ....

When did you start learning your second language? ....

How long have you been learning your second language? ....

How often do you speak your second language? ....

How regularly do you read in your second language? ....

In the scale below give an estimation of your comprehension level (reading and listening) in your second language

Very low	Low	Medium Low	Medium	High	Very high	As a native speaker
1	2	3	4	5	6	7

In the scale below give an estimation of your production level (writing and speaking) in your second language

Very low	Low	Medium Low	Medium	High	Very high	As a native speaker
1	2	3	4	5	6	7

Appendix B

Edinburgh Handedness Inventory (Oldfield, 1971)

Handedness Questionaire

Instructions

Please indicate your preferences in the use of hands in the following activities

If you are really indifferent, select "Either".

Where the preference is so strong that you would never try to use the other hand select "No".

When:	Which hand do you prefer?	Do you ever use the other hand?
Writing:	L | R | either	Yes | No
Drawing:	L | R | either	Yes | No
Throwing:	L | R | either	Yes | No
Using scissors:	L | R | either	Yes | No
Using a toothbrush:	L | R | either	Yes | No
Using a knife (without fork):	L | R | either	Yes | No
Using a spoon:	L | R | either	Yes | No
Using a broom (upper hand):	L | R | either	Yes | No
Striking a match:	L | R | either	Yes | No
Opening a box (lid):	L | R | either	Yes | No

Appendix C

Stimuli from Experiments 1 and 2

Short words

area	baby	band	bank
base	beat	beer	bell
bend	bill	bird	blow
boat	body	bomb	bone
boom	bowl	bull	bush
cafe	call	card	cash
cave	chin	club	code
cold	copy	data	date
dawn	deer	desk	diet
dish	down	duty	even
evil	face	fact	fall
fear	film	find	fire
fish	five	flag	food
form	game	gang	girl
glow	golf	hair	hall
hand	heat	hell	hole
home	hook	hour	king
lady	lamp	last	line
love	meat	mind	news
note	oven	page	part
pick	plan	play	poet
post	race	rain	rock
safe	sale	seat	ship
shot	skin	song	star
step	tail	task	team

bafe	bife	bong	bont
bune	carn	cint	dask
dath	dirs	drad	eads
fert	fike	fise	flal
flar	foof	fump	gabe
gelt	gink	gite	gome
gose	gren	grig	guck
haid	harb	hern	hong
jall	jart	jeek	jold
joms	kice	lasp	lels
lems	libe	lonk	lork
mafe	marb	mobe	moom
mout	nean	nend	nies
ning	nipe	nons	nust
peen	rark	rolt	rorn
sabe	samp	seaf	sebs
slas	sloy	slub	smot
snat	soin	sool	sork
spab	stat	sust	tarl
thad	tirs	tuds	turt
vads	vaze	ving	vink
vock	vods	vose	warb
wegs	wibs	wote	woys
yame	ying	yink	yuck
zale	zall	zank	zoes

Long words

academic	addition	activity	advisers
argument	agencies	assembly	alliance
attitude	basement	biscuits	audience
building	chickens	colleges	brothers
creature	chairman	computer	consumer
customer	cupboard	darkness	daughter
decision	delivery	director	district
division	employer	everyone	election
envelope	exercise	festival	evidence
football	governor	eyebrows	forehead
garments	illusion	language	generals
managers	material	hospital	hundreds
industry	learning	medicine	northern
majority	officers	ordinary	marathon
painting	merchant	military	pavement
missiles	peasants	personal	movement
original	physical	painters	planning
platform	passport	pleasure	potatoes
presence	practice	prisoner	princess
problems	producer	property	question
refugees	reaction	religion	reporter
sergeant	solution	response	security
suitcase	sunshine	servants	teachers
students	thinking	sunlight	vehicles
tourists	vitamins	treasury	woodland

blimpsed	brelched	brorched	brotched
braughts	choughts	cheathed	crooched
climpsed	dretched	dwenched	craughts
flutched	crounced	froached	frouched
frinched	gaunched	gheathed	phrashed
ghurched	granched	pletched	prouched
jaunched	prunched	scanched	scrabbed
phatched	planched	prelched	scrermed
scrawked	scrimmed	screased	scroamed
scrooled	scrowled	screeced	scutched
shragged	scrumbed	sheached	sherthed
shriefed	shrummed	shropped	skerched
smetched	snoothed	shrudged	skenched
speathed	splassed	slooched	splurfed
splurled	slounced	spranned	squeered
smanched	smeathed	straired	smorched
sninched	spetched	splained	strigged
strirped	splulged	sporched	sprawped
stromped	strooped	strorled	strumped
sprighed	spripped	sprounge	strassed
thrasped	thrieked	strissed	thrilmed
thrugged	thurched	thwanked	strugged
tharched	thwilled	trounged	threched
twinched	twotched	througed	whurched
wrerthed	thwucked	wrouched	trouched

Appendix D

Stimuli from Experiments 3, 4 and 5

4 Letter fillers	4 Letter Late OUP	7 Letter Early OUP	7 Letter Late OUP
army	arch	anagram	abscess
balm	atom	biscuit	algebra
calf	axle	ceiling	chamber
deer	buzz	cistern	console
fang	data	cyanide	curtain
gear	duty	darling	decimal
hair	echo	dolphin	destiny
junk	exam	emperor	embassy
lane	hymn	fritter	fashion
lamb	icon	garment	feather
meal	inch	hormone	harbour
oath	iota	javelin	initial
pier	kiwi	knuckle	leather
rash	knee	poverty	royalty
scar	liar	pyramid	scallop
stew	menu	rhubarb	surgery
tent	oboe	sausage	syringe
tomb	tuft	tuition	thistle
wall	urge	welfare	thunder
wolf	void	yoghurt	vacancy

4 Letter Non-words	4 Letter Non-words	7 Letter Non-words	7 Letter Non-words
clav	yoan	smemmed	frooths
goid	lulb	phriced	sheened
jusk	pote	sprince	shrores
ifed	talp	splusks	weached
dowd	zawp	thasked	whelved
pess	kund	wroaned	shrurnt
nins	hoid	phlorse	snaphed
thad	briv	shrypts	yeached
smet	joff	prombed	knuzzed
hipt	nurf	crarced	nooched
chon	skub	shrinns	ghourth
nalt	wirp	whauced	phlelve
plag	poft	scoofed	noached
fimp	feak	scraunt	thromes
celm	pult	bloaves	glieves
unks	plog	prordes	gwurved
zine	blit	scuints	shelped
rhel	sisk	sprasks	psunged
jelm	weff	dwighed	trunged
soin	yain	scrince	frooths

Appendix E

Stimuli from Experiment 6

WORDS				NON-WORDS			
Short Pointed	Long Pointed	Short Unpointed	Long Unpointed	Short Pointed	Long Pointed	Short Unpointed	Long Unpointed
אֶבֶן	אֲבַטִּיחַ	אגס	אימרה	אַקָּן	הַטְנָעָה	בצח	בבדוק
אֶרֶץ	אַרְנֶבֶת	בוץ	ארובה	בּוֹט	הַלְחָפָּה	חזא	ויוכר
בְּאֵר	הַבְטָחָה	בור	חביתה	גַּעַךְ	הַשְׁלָאָה	חפי	ועדיר
בָּרָק	כַּרְטִיס	גדה	לטיפה	דַּיִס	חַשְׁוְבָּן	יסק	כתורק
בּוּל	לְחִימָה	גמד	מטלית	דְּחָל	לַחְוִית	כות	לובלה
גָּדֵר	לְחִישָׁה	דוב	מלאכה	הַדָּז	מְאוֹכָב	לות	מדירף
דְּבַשׁ	לְקִיחָה	דלי	מסחטה	טוֹחַ	מְצַאיָה	ליו	מטמכה
דֶּבֶק	מְדִידָה	כור	מעבדה	יֶלֶא	מַבְּחֶרֶת	לצת	ממשרל
וֶתֶק	מִבְרֶשֶׁת	מגף	מקטרת	לְדָשׁ	מַהֲנִיג	מזר	מרעכת
חוֹל	מִסְעָדָה	מדף	מרגמה	לֶמַּח	מַמְאִין	מחב	משחלן
טִיב	מַאֲפֵרָה	מסך	משאבה	מֶרֶג	מַפְשְׁחָה	מיר	סיוכי
כָּתֵף	מַבְחֵנָה	מפל	עתירה	מָשֶׁף	מַשְׁלִין	מלת	עלדוה
מִיץ	מַכּוֹלֶת	נמל	פסנתר	נֶפֶּן	מַשְׁבְּאָה	נמע	פיקסה
מַסָּע	מַצְלֵמָה	נמר	פרוסה	נַעַב	נִיסְעָה	סיא	שיפות
נַחַל	מָסוֹרֶת	עקב	רמזור	נוּק	נַסְכְּיָה	עכם	שלוגך
סֶגֶל	מוּעָקָה	פאה	שארית	סֶרַךְ	עַיָּלוֹן	רגד	שליבם
פְּאֵר	עֲקִירָה	קמט	שושלת	צְלֵר	עַתְרַבּוֹ	שוג	ששבגת
פְּרִי	פְּגִיעָה	קפל	תחביב	קֻרָז	רִימְשָׁה	תיו	תושבא
צֶלַע	צְבִיעָה	שפן	תקומה	רוֹג	רִיעוֹן	תכק	תושרה
שִׂיחַ	תְּפִירָה	תרד	תקליט	שֵׁזָק	רִפְאָוָה	תצו	תקיול
אָגָם	אַחֲרִית	אבק	אגרטל	אוֹק	גְלוֹגָל	בעס	אמרון
בָּצָל	אַלְבּוֹם	במה	אצולה	בְּרוֹ	חֶלְקַאי	וצע	בושרה
בָּרָד	בִּיקְתָּה	בצק	בחילה	דֶּשֶׁל	לִקְחִיָּה	ושק	דארון
זְאֵב	חֲפִיסָה	חור	בעיטה	וִיעַ	מְדוּעָה	זקל	החפלה
טַחַב	כְּבִיסָה	חכם	מדפסת	זַגָּל	מְיוּשָׁשׁ	זשב	הכרבה
טוּר	כְּבֵדוּת	חצר	מדרגה	זָקַי	מִידְנָה	חבן	הסיוס
יֶרֶק	לְחִיצָה	חרם	מזכרת	יָנָב	מִיסְרָה	חרח	מאימן
מֵשִׁי	מְאוּרָה	יער	מכשיר	לֶכֶג	מִלְצְמָה	יטג	מטרוף
מַחַק	מְלוּכָה	כלב	ממשלה	לֶמַח	מַבְדָּקָה	יעם	נשמיה
מָקֵל	מִקְלֶדֶת	מגש	מקפצה	לַחַס	מַגְלִיָּה	ירל	סופרט
נֶתַח	מַלְתֵּחָה	מדע	משולש	לָפִי	מַרְזוּן	לטי	פורסה
סֶלַע	מַעֲטֶפֶת	מוט	עצבות	נָחָב	נֶסְעָיָה	נבש	ציוכם
סַפָּה	מַשְׁתֵּלָה	מחט	עצירה	נוֹא	פַּצְרִיָּה	ניט	קוספה
סָלָט	סְטִירָה	מצח	עקיפה	פִּיעַ	פְּאתוֹם	סיט	קטיון
פֶּרֶא	סוֹלְלָה	מרד	פיסקה	פֶּגֶל	קִירְנָה	סעט	שגמיה
פָּנָס	קְלִיפָּה	נפט	צפירה	צִיב	רְאָוִין	פסי	שרותט
צֶמֶד	קוּפְסָא	עמל	צפרדע	קֶצֶם	שִׁיאָפָּה	ציב	תובאה
צֶמֶר	שְׁקֵדִיָּה	עשב	תבואה	רָקָף	שִׁיגֶאָה	צתר	תולנה
קֶמַח	תַּבְשִׁיל	קיר	תחביר	שֶׁנָם	שׁוֹלֶשֶׁת	קעה	תעבוה
שַׁעַל	תַּרְדֵּמָה	קשב	תכסיס	תוֹז	תְּעוֹלֶת	שמל	תפמיה

Appendix F

Stimuli from Experiment 7

English

Short Words	Long Words	Short NW	Long NW
beak	airport	ambey	angious
boom	cricket	bole	archard
calf	cushion	celly	brawket
camel	dentist	chown	calvium
candy	eyeball	crowl	comdass
cigar	grenade	curpy	frystal
cloak	griddle	deek	furglar
frock	harbour	driss	gansion
grin	leopard	lale	hampock
lump	lettuce	leab	harmest
mask	measles	lurse	mustary
moss	missile	phess	plitter
pope	rainbow	phine	prethel
robe	sausage	rived	rehicle
spark	scalpel	slear	spuggle
swamp	slipper	smule	sturble
tank	tractor	snar	swallot
vicar	traffic	snup	tambler
wagon	trimmer	sping	trauser
wound	trinket	swib	travier

Welsh

Short Words	Long Words	Short NW	Long NW
afal	allwedd	amlyn	adeilall
asyn	brechdan	barw	athrawedd
broga	cannwyll	bwedd	canegan
cadno	ceiliog	cacyn	cefnfodd
carw	ceirios	calod	chwistreg
cnau	chwiban	clyrt	corflun
coron	cwningen	cridd	darlyth
cwmwl	cyllell	dren	dynulliad
dafad	ffenestr	floch	esgwthr
drws	ffynnon	fys	gwargod
dryll	grawnwin	haneg	gwyegys
eryr	hwyaden	hesan	hwniadur
gafr	llygoden	heul	hwyddog
mefus	morgrug	llar	mynadfa
neidr	mwrthwl	llig	prifywgol
paun	nodwydd	myron	swyddla
peren	rhewgell	paeth	yngraff
pib	sbectol	tagen	ysgoden
seren	tylluan	troyn	ysgubon
telyn	wnionyn	ysgid	ystafeg

Appendix G

Stimuli from Experiments 8 and 9

Spanish Words

acto	laúd	acné	hiel
agua	leño	acta	hoyo
aire	lupa	afán	humo
alud	maíz	amas	iglú
arco	menú	amor	isla
aval	miel	anís	jugo
azar	mili	área	nene
baúl	nave	arma	neón
caos	niña	arpa	nuez
crío	niño	asno	obra
dote	oboe	atún	ocio
emir	ojal	aula	oído
éter	olmo	axis	olla
fuel	opio	bebé	olor
giro	piel	bici	orín
goce	plan	brío	papá
golf	raíz	cima	raíl
guía	reja	cinc	rape
hipo	sebo	clan	sima
hule	sede	daño	tabú
idea	sexo	dedo	taxi
imán	test	edad	tren
iris	yema	flor	urbe
juez	yodo	fuga	vaho
kilo	zumo	heno	zoco

acte	fima	biro	maoz
aola	fror	bito	mien
arsa	gaho	dazo	moga
bama	hama	doya	mosa
bila	icto	edio	mujo
buse	irco	flave	nedo
cafa	jaso	gada	nijo
cais	loda	geso	nita
cema	nala	guea	obza
choka	nalle	hara	opal
cige	nera	heclo	pamo
cila	noro	hicha	raca
dabo	prio	holo	rilla
damo	pubo	ipea	rilla
dano	safe	jiez	ruto
dasa	sata	jife	secho
dena	selo	joma	sozo
dima	valke	kado	tisa
dosa	vema	kumo	usla
duga	vema	laro	vema
edod	voco	lecre	veva
enye	vuga	lloma	vodo
euge	xaro	llono	voja
euto	zeso	lore	vuno
faño	ziel	luon	zama

almohada	estética	anatomía	invierno
almuerzo	facultad	apertura	juventud
análisis	fantasma	ayudante	muchacho
atención	gimnasia	banquete	objetivo
ausencia	guerrero	cabecera	paciente
aventura	herencia	camarero	paradoja
biología	historia	castillo	pariente
borracho	lenguaje	consulta	plástico
cantante	libertad	contacto	polémica
carencia	marinero	contrato	política
cenicero	material	cualidad	pretexto
comisión	monstruo	descanso	profesor
concepto	muchacha	descarga	programa
conducta	murmullo	despacho	religión
consuelo	nacional	discurso	renuncia
contexto	pantalla	doncella	silencio
creación	político	elección	sorpresa
denuncia	potencia	empleada	sucesión
desierto	presente	escritor	superior
destello	proyecto	estación	temporal
destreza	revólver	filósofo	teniente
detenido	revuelta	gravedad	terminal
doctrina	señorito	guitarra	tontería
elefante	suciedad	heredero	universo
encierro	vendedor	impuesto	vocación

acadesia	claradad	buestión	elicacia
adhosión	clauspro	conrunto	elimento
afunidad	colercio	criserio	embajaca
amplitad	comierzo	cronisfa	ensienda
analogio	concurmo	cualidap	entiarro
apertuga	conducna	cucrillo	ercetera
arandono	consogna	cudierta	erditaño
arsiculo	conticto	decosión	escrigor
asarblea	contigio	desapuno	escupeta
atección	copardia	desistre	esduerzo
atribato	coracter	desordon	esgomago
ausincia	corcania	devacion	esjectro
badquete	cortusia	dexcuido	espación
barborie	cosgreso	dictamel	esparitu
brecedad	creanion	difubion	estoncia
calavura	creuncia	discurpa	evonomia
camalogo	cuntidad	divercio	facumtad
cansulta	damarada	doncilla	fantasva
capriche	demosito	doscanso	fantatia
cardesal	elmuerzo	driatura	farmacoa
catebral	garanzia	edifacio	fasbismo
ceaccion	onsiedad	edisodio	fenumeno
centaria	pomision	eftimulo	fifosofo
ceudillo	ponducto	ejerciro	pistrito
chocolite	vontorno	eleccior	vermento

English words

area	baby	band	bank
base	beat	beer	bell
bend	bill	bird	blow
boat	body	bomb	bone
boom	bowl	bull	bush
cafe	call	card	cash
cave	chin	club	code
cold	copy	data	date
dawn	deer	desk	diet
dish	down	duty	even
evil	face	fact	fall
fear	film	find	fire
fish	five	flag	food
form	game	gang	girl
glow	golf	hair	hall
hand	heat	hell	hole
home	hook	hour	king
lady	lamp	last	line
love	meat	mind	news
note	oven	page	part
pick	plan	play	poet
post	race	rain	rock
safe	sale	seat	ship
shot	skin	song	star
step	tail	task	team

bafe	bife	bong	bont
bune	carn	cint	dask
dath	dirs	drad	eads
fert	fike	fise	flal
flar	foof	fump	gabe
gelt	gink	gite	gome
gose	gren	grig	guck
haid	harb	hern	hong
jall	jart	jeek	jold
joms	kice	lasp	lels
lems	libe	lonk	lork
mafe	marb	mobe	moom
mout	nean	nend	nies
ning	nipe	nons	nust
peen	rark	rolt	rorn
sabe	samp	seaf	sebs
slas	sloy	slub	smot
snat	soin	sool	sork
spab	stat	sust	tarl
thad	tirs	tuds	turt
vads	vaze	ving	vink
vock	vods	vose	warb
wegs	wibs	wote	woys
yame	ying	yink	yuck
zale	zall	zank	zoes

academic	addition	activity	advisers
argument	agencies	assembly	alliance
attitude	basement	biscuits	audience
building	chickens	colleges	brothers
creature	chairman	computer	consumer
customer	cupboard	darkness	daughter
decision	delivery	director	district
division	employer	everyone	election
envelope	exercise	festival	evidence
football	governor	eyebrows	forehead
garments	illusion	language	generals
managers	material	hospital	hundreds
industry	learning	medicine	northern
majority	officers	ordinary	marathon
painting	merchant	military	pavement
missiles	peasants	personal	movement
original	physical	painters	planning
platform	passport	pleasure	potatoes
presence	practice	prisoner	princess
problems	producer	property	question
refugees	reaction	religion	reporter
sergeant	solution	response	security
suitcase	sunshine	servants	teachers
students	thinking	sunlight	vehicles
tourists	vitamins	treasury	woodland

blimpsed	brelched	brorched	brotched
braughts	choughts	cheathed	crooched
climpsed	dretched	dwenched	craughts
flutched	crounced	froached	frouched
frinched	gaunched	gheathed	phrashed
ghurched	granched	pletched	prouched
jaunched	prunched	scanched	scrabbed
phatched	planched	prelched	scrermed
scrawked	scrimmed	screased	scroamed
scrooled	scrowled	screeced	scutched
shragged	scrumbed	sheached	sherthed
shriefed	shrummed	shropped	skerched
smetched	snoothed	shrudged	skenched
speathed	splassed	slooched	splurfed
splurled	slounced	spranned	squeered
smanched	smeathed	straired	smorched
sninched	spetched	splained	strigged
strirped	splulged	sporched	sprawped
stromped	strooped	strorled	strumped
sprighed	spripped	sprounge	strassed
thrasped	thrieked	strissed	thrilmed
thrugged	thurched	thwanked	strugged
tharched	thwilled	trounged	threched
twinched	twotched	througed	whurched
wrerthed	thwucked	wrouched	trouched

Appendix H

Stimuli for Experiments 10 and 11

Short Words	Long Words	Short NW	Long NW
ache	rainbow	jead	blophed
bait	section	aved	dweutts
bell	sausage	tomp	rhoaque
cape	trainer	wuls	gaigged
chin	billion	imfs	jinthed
dame	address	koid	driefed
dust	dentist	afes	fraulds
fist	compass	yoge	frourle
gate	cricket	skam	peembed
herb	squeeze	mish	stoambs
joke	calcium	jomp	meupped
lake	comment	awnd	ghlorns
coup	steward	jiem	ghlofth
mess	orchard	tane	shraved
note	trailer	bynt	dweamms
peak	coaster	juzz	thendge
shoe	boycott	nesk	dworced
slab	session	solt	krobbed
team	auction	smey	slounns
turf	tribute	virn	shoande
apex	eyeball	zang	rherque
gene	silence	dwoo	throfts
belt	tractor	skez	phrerph
card	slipper	mege	sckybbs
chip	command	kilp	rhulmed
data	storage	psue	plesped
drug	lettuce	yult	barpths
film	stomach	dolb	kindged
gear	mistake	voff	ghreuls
hood	cushion	kark	gwarnes
junk	traitor	heen	gwaumed
list	nucleus	drot	screfed
mail	baggage	targ	brawsts
moon	harbour	twuy	dwoffth
park	leopard	wurb	crilfed
pipe	hammock	jeag	bloaped
seed	cathode	pove	bloules
sofa	stumble	smus	shrelps
trap	welfare	hosh	shreene
weed	version	fark	blainds
atom	climate	slok	fraiged
beef	theatre	spis	rharfes
bump	airport	toct	scrolch
cash	disease	gilv	shaugue
cave	culture	rhud	dorcked
jury	ceiling	squa	brownts
dose	missile	telb	dryntce
fuel	kingdom	hilf	ghlunze
gold	vehicle	norv	squolns
heel	burglar	prot	kroarms
jail	crystal	nysc	sprourv
lace	poultry	vewt	dwoppth
mate	traffic	enck	sckrune
mood	network	jatt	ploodds
path	granite	swip	skinsed
pony	captive	movs	swucsts
sink	hallway	glis	gheudge
soup	lecture	garl	screest
tube	platter	grev	krouled
ward	symptom	dwat	flesked